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Inventory of Repairing and Strengthening Techniques for Masonry Arch Bridges

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I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

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DEDICATION

To my parents, for all their hard work, support, and prayers.

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ABSTRACT

Inventory of Repairing and Strengthening Techniques in Masonry Arch Bridges:

Bridges have been important throughout history in connecting cultures, sharing ideas, and providing the backbone of transportation networks. It is necessary to restore and preserve these structures for their particular functionality and cultural heritage value. The focus of this paper is to present and discuss the many ways of strengthening and repairing masonry arch bridges ranging from minimum intervention to complete reconstruction. It is meant to provide a guide for engineers and architects on the methods available and the advantages and disadvantages of these methods, and to assist in their decisions of masonry arch bridge conservation.

The ideas in this paper are presented in a way to help the engineer choose an intervention which allows an improvement in performance and preservation of cultural heritage value. A brief overview of the evolution of arch construction and the progression of understading the capacity of an arch are first discussed. Common damages to masonry arch bridges are briefly discussed, as well as possible causes. Further, investigation and diagonsis techniques which may be used to determine damages and their causes are discussed. The main focus is on understanding and comparing different methods of strengthening and repairing masonry arch bridges. Two case studies were selected to discuss and demonstrate the application and process of various methods.

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RESUMO

Inventario de Técnicas de Reparación y Reforzamiento en Puentes Arco de Albañilería:

Los puentes han sido muy importantes a lo largo de la historia, conectando culturas, compartiendo ideas, y siendo una de las más importantes infraestructuras de los medios de transporte. Es necesario restaurar y preservar estas estructuras según su particular función y su valor cultural. El enfoque del presente documento es mostrar y comentar diversas maneras de reforzamiento y reparación en puentes arco de albañilería, desde una mínima intervención hacia una completa reconstrucción de la infraestructura. El objetivo de la presente tesis es proveer a los ingenieros y arquitectos una guía sobre los métodos disponibles y de las ventajas y desventajas de esos métodos, además de asistirlos en sus decisiones respecto a la conservación de puentes arco de albañilería.

Las ideas en este documento son presentadas de manera que pueda ayudar al ingeniero a escoger una intervención que permita el mejoramiento del comportamiento y preservación del valor cultural de la estructura. Un breve repaso de la evolución de la construcción de arcos y del progreso en comprender la capacidad de un arco, es discutido en la primera parte del documento. Daños comunes a los puentes arco de albañilería son brevemente discutidos, así como sus posibles causas. Posteriormente, investigaciones y diversas técnicas de diagnosis que pueden ser utilizadas para determinar daños y sus posibles causas son discutidas. El principal enfoque esta en comprender y comparar diferentes métodos de reforzamiento y reparación de puentes arco de albañilería. Dos casos de estudios fueron seleccionados para la discusión y demostración de la aplicación y proceso de diversos métodos.

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1. INTRODUCTION

Conservation of architectural heritage structures has become an increasingly important in the construction and engineering world. Conservation involves the actions and processes that are aimed at safeguarding the character-defining elements of a cultural resource so as to retain its heritage value and extend its physical life (proposed definition for ISO 13822 on heritage structures). As defined by the UNESCO convention in 1972, architectural heritage includes architectural works, elements or structures of an archaeological nature, and groups of separate or connected buildings. Many of these heritage locations provide economic stimulus through tourism, however, many more are structures that provide housing, the infrastructure of a city such as transportation networks, water and waste, and for religious purposes. Beyond the particular use of the structure, each structure contributes its own value to cultural heritage. These values include, but are not limited to, technical, artistic and spiritual merits, identity to cultures, world regions and towns, economic resources and contribution to cultural diversity. Humans like to connect with the past through these structures, especially when it may have a symbolic meaning to them.

A good example of this shown in Figure 1.1 is the Ponte Vecchio in Florence. The bridge is not only a point of interest for tourists, but it is important to the people of Florence. Originally opened in 996 A.D. and last rebuilt in 1345 A.D., the bridge is the only surviving bridge after the 2nd World War that runs across the river. For an unknown reason, the Nazis did not destroy Ponte Vecchio. Thus, the bridge remains as the only “true” bridge of antiquity in Florence; that is to say, it has not been rebuilt in modern times. For this reason, it is important to the people of Florence and for the cultural heritage of the city.

Figure 1.1: Ponte Vecchio, Florence, Italy (photo by: Thomas Beuerman)

Similarly, and perhaps an even stronger example is the Stirling Bridge (Figure 1.2) in Scotland. The bridge is the location of the Battle of Stirling Bridge in which Andrew Moray and William Wallace defeated the combined English forces of John de Warenne, 7th Earl of Surrey and Hugh de Cressingham , on September 11, 1297. The battle was the First War of Scottish Independence. Although this bridge is not used as an important transportation link today, every Scot shares a personal connection with this bridge as it symbolizes the beginning of their fight for independence. Therefore, it is very important to their cultural heritage and should be maintained and preserved.

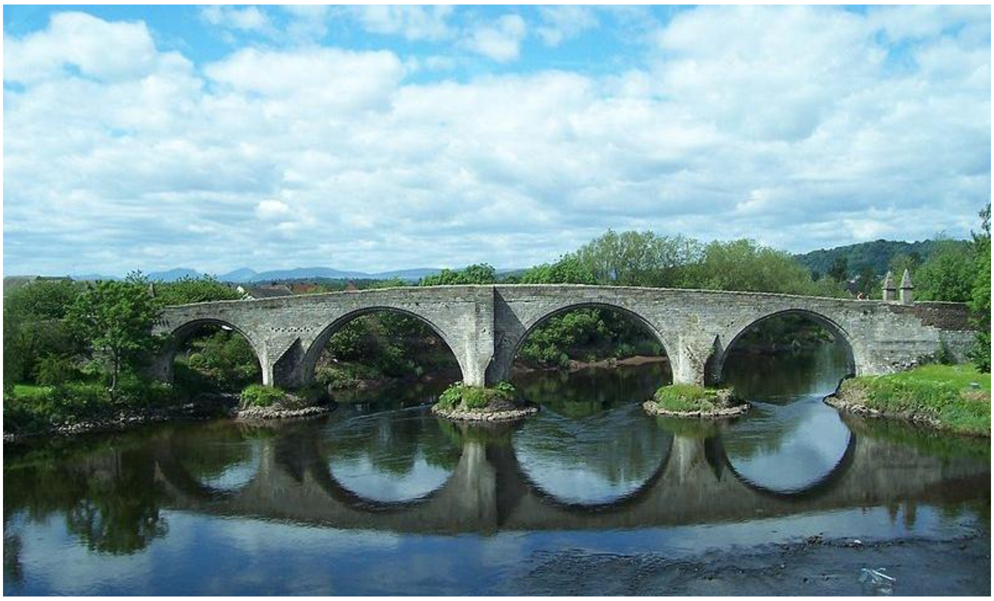


Figure 1.2: Stirling Bridge, Scotland. (photo by: David Meisner, 2006)

In the attempt to define and provide guidelines for historical conservation, several committees and conferences have been held to create such documents. Some of these include the Athens Charter in 1931, the Venice Charter in 1964, the European Charter of Architectural Heritage in 1975, The Nara Charter of 1994 and the ICOMOS General Assembly in 2003. The Nara Charter of 1994 describes cultural and heritage diversity as following:

- The diversity of cultures and heritage in our world is an irreplaceable source of spiritual and intellectual richness for all humankind. The protection and enhancement of cultural and heritage diversity in our world should be actively promoted as an essential aspect of human development.

- Cultural heritage diversity exists in time and space, and demands respect for other cultures and all aspects of their belief systems. In cases where cultural values appear to be in conflict, respect for cultural diversity demands acknowledgment of the legitimacy of the cultural values of all parties.
- All cultures and societies are rooted in the particular forms and means of tangible and intangible expression which constitute their heritage, and these should be respected.
- As from the UNESCO fundamental principle: the cultural heritage of each is the cultural heritage of all. Responsibility for cultural heritage and the management of it belongs, in the first place, to the cultural community that has generated it, and subsequently to that which cares for it.

Thus, the importance of conservation is evident. However, the appropriate methods to use are not also so evident. Two terms encompass conservation; preservation and restoration. Preservation is an action or process of protecting, maintaining, and/or stabilizing the existing materials, form, and integrity of a cultural resource or of an individual component, while protecting its heritage value. Restoration is an action or process of accurately revealing, recovering, or representing the state of a cultural resource or of an individual component, as it appeared at a particular period in its history, while protecting its heritage value (Roca and Bláha, 2008). Both preservation and restoration include methods by which a structure can be strengthened or repaired for the improvement of its designated purpose. However, with both the question of authenticity is presented.

The authenticity of a monumental building is a broad concept that, aside from its history, aesthetic value and social significance, is extended to the structure itself (Pinto, 2008).

The Nara charter of 1994 presents the following on authenticity:

- Conservation of cultural heritage in all its forms and historical periods is rooted in the values attributed to the heritage. Our ability to understand these values depends, in part, on the degree to which information sources about these values may be understood as credible or truthful. Knowledge and understanding of these sources of information, in relation to original and subsequent characteristics of the cultural heritage, and their meaning, is a requisite basis for assessing all aspects of authenticity.
- Authenticity, considered in this way and affirmed in the Charter of Venice, appears as the essential qualifying factor concerning values. The understanding of authenticity plays a fundamental role in all scientific studies of the cultural heritage, in conservation and restoration planning, as well as within the inscription procedures used for the World Heritage Convention and other cultural heritage inventories.
- All judgments about values attributed to cultural properties as well as the credibility of related information sources may differ from culture to culture, and even within the same culture. It is

thus not possible to base judgments of values and authenticity within fixed criteria. On the contrary, the respect due to all cultures requires that heritage properties must be considered and judged within the cultural contexts to which they belong.

- Therefore, it is of the highest importance and urgency that, within each culture, recognition be accorded to the specific nature of its heritage values and the credibility and truthfulness of related information sources.
- Depending on the nature of the cultural heritage, its cultural context, and its evolution through time, authenticity judgments may be linked to the worth of a great variety of sources of information. Aspects of the sources may include form and design, materials and substance, use and function, traditions and techniques, location and setting, and spirit and feeling, and other internal and external factors. The use of these sources permits elaboration of the specific artistic, historic, social, and scientific dimensions of the cultural heritage being examined.

The ICOMOS *International Scientific Committee for the Analysis and Restoration of Structures of Architectural Heritage* (ISCARSAH) followed in 2001 with these recommendations:

- Respect of original materials, morphology and structural arrangement
- Respect for distinguishing qualities of structure and environment deriving from original form
- Respect for original concept, materials and construction techniques
- Respect for significant subsequent (historical) changes
- Respect for alterations or imperfections (deformations) that have become part of the history of the structure provided that they do not compromise the safety requirements.

In 2003, ICOMOS incorporated these ideas and those from the Nara Charter and the Venice Charter to create the document *Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage*.

There is much controversy over authenticity and it is difficult to claim that one particular notion is correct for all cases. Some people want to see the structure as it was in its highest splendor, even if that requires reconstruction of some elements with new material. Others argue that this completely ruins the authenticity and significance of the structure and the absolute minimum intervention is the correct way to approach any conservation project. There are many degrees between these two extremes some point at which engineers, architects and other parties involved with a particular project must come to an agreement.

Following the 2nd World War, there was massive destruction to monuments and buildings of all types around Europe. This has caused a particular controversy as to how these structures should be approached. Many of the structures are too damaged to simply be preserved by minimal intervention; in fact many lay in complete ruins. Now there is an issue of whether the structure should be replaced by another or rebuilt to however necessary in order to preserve some sense of authenticity.

The fact is that many of the structures are, whether damaged by war, natural deterioration or other causes, still needed to provide a particular service to the community in which it is located. Sometimes, a minimum intervention will not allow this service to continue. In other cases, an emergency intervention is necessary in order to keep the structure from failing. Thus, the sense is that each project is unique, and its particular solution must be determined by the engineers, architects, the community and other parties involved, in a manner that allows the structure to function as it is needed, as well as to follow the guidelines set forth by the ICOMOS document.

With masonry arch bridges the focus of this paper, there is not only a connection people can feel with the past, but a physical connection across some geographical feature. Bridges certainly provide a particular service whether for transportation networks, carrying people and vehicles, or aqueducts carrying water. As aqueducts are mainly left as marvels of the past, bridges which are used for transportation networks (both pedestrian and vehicular) can cause controversy in conservation. With the increase of live loads, both in weight and frequency, the need for a wider roadway or other improvements, or damages from many possible sources and from many years of weathering, conservation works are usually required.

Some may suggest replacing the bridge with a modern design which can easily provide for the necessary demands. However, many people enjoy the look and historical meaning of the bridge, and desire it to remain as is. Again, between these two extremes, the engineers, architects, and other parties involved (as conservation requires a multi-disciplinary approach) must come to an agreement that satisfies the demands of the bridge and the principles of conservation and authenticity mentioned previously.

As seen in the Mostar Old Bridge rehabilitation in Bosnia, sometimes rebuilding is the only option in conservation. As bridges are important transportation links, they are often major targets during time of war. This was the case in 1993 for the Mostar Old Bridge that was demolished during military operations. Started in 1557 and completed nine years later, became an inspiration for architectural and structural art, paintings, musical and other kind of art. The bridge had been ranked among the greatest historical monuments on the Balkans. Thus, in this case it was necessary to preserve the original form of the completely destroyed bridge (Figure 1.3) by reconstruction. Ruins from the river were implemented in the construction where possible, to provide authenticity. The remaining structure was rebuilt using like materials to the original construction.

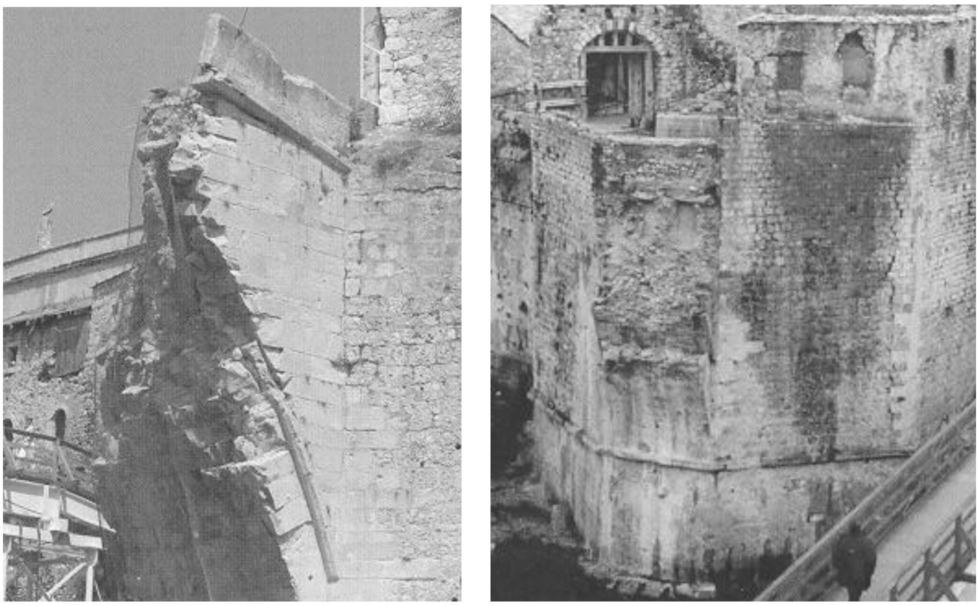


Figure 1.3: Destroyed Old Bridge – right and left bank (Žderić, 2007)

Figure 1.4: Reconstructed old bridge (photo by: Víctor González)

On the other hand, the restoration of Pont Trencat near Barcelona had different demands for intervention. In 1811, during the Napoleonic Wars, the main arch of this bridge was destroyed. It was left in its ruined state (Figure 1.5) until 1996 when restoration funds were raised. As the goal was to recover the functionality of the bridge for pedestrian use, and there was no great significance in its original form, it was not seen necessary to rebuild the bridge. In fact, nobody is sure of its original shape since it has been in ruins for many generations; the name of the bridge itself, “El Pont Trencat” is translated “The Broken Bridge”.

Figure 1.5: The remains of “Pont Trencat” (Font, 2001)

Therefore, it was determined that the better intervention would be to construct the missing part with a modern structure, connected to the older part (Figure 1.6). This results in a functional bridge that preserves the authenticity of the remaining bridge.

Figure 1.6: Completed Pont Trencat Intervention (Font, 2004).

In both examples, the results respect the guidelines and provide the functionality needed. This does not mean that there was no controversy in the final decision, but the parties involved in the conservation work provided the solutions which met the demands of the project while respecting the guidelines.

Bridges have been important throughout history in connecting cultures, sharing ideas, and providing the backbone of transportation networks. It is necessary to restore and preserve these structures for their particular functionality and cultural heritage value. The focus of this paper is to present and discuss the many ways of strengthening and repairing masonry arch bridges ranging from minimum intervention to complete reconstruction. It is meant to provide a guide for engineers and architects on the methods available and the advantages and disadvantages of these methods, and to assist in their decisions of masonry arch bridge conservation.

2. MASONRY ARCH BRIDGES

2.1 History

Archaeological remains of stone arch bridges date back to the Sumerian civilization in Mesopotamia, around 2000 B.C. The Sumerians assembled stones in the shape of an arch allowing them to work in compression rather than in bending as a beam bridge. These arch bridges were not the typical radial arrangement of stone segments, but more of a false arch (corbel arch) composed of cantilevered brick or stone progressively jutting out (Figure 2.1). Possibly the oldest existing arch bridge is the Mycenaean Arkadiko bridge (Figure 2.2) in Greece built around 1300 B.C. Although the arch was already discovered and known by the Etruscans and Greeks, the Romans were the first to fully utilize the potential of arches in bridge construction. The Romans turned the masonry arch into the almost universal method of bridge construction until the 18th century. Many of these bridges are still standing today and even used for modern traffic loads.

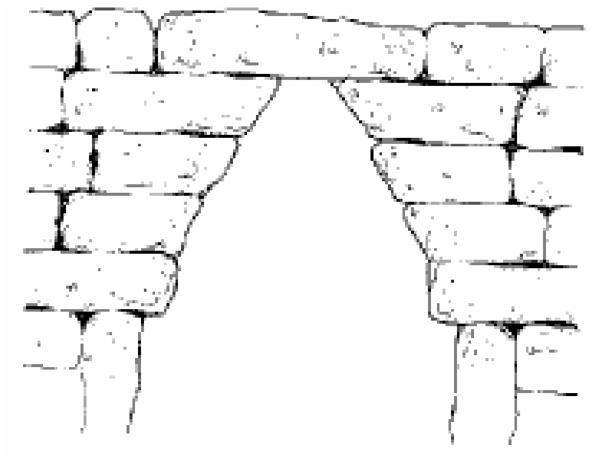


Figure 2.1: A corbel (or false) arch. (Bláha, 2008)

Figure 2.2: Arkadiko Bridge. (photo by: David Gavin)

The original Roman arches were semi-circular in shape (Figure 2.3a) made with wedge-shaped stones (voussoirs) of the same size and shape. The segmental arch (Figure 2.3b) forms a partial, semi-elliptical curve, or eyebrow, and has a slight rise. This type of arch also appeared in some Roman bridges and allowed larger amounts of flood water to pass under the bridge, lowering the risk of being swept away in floods.

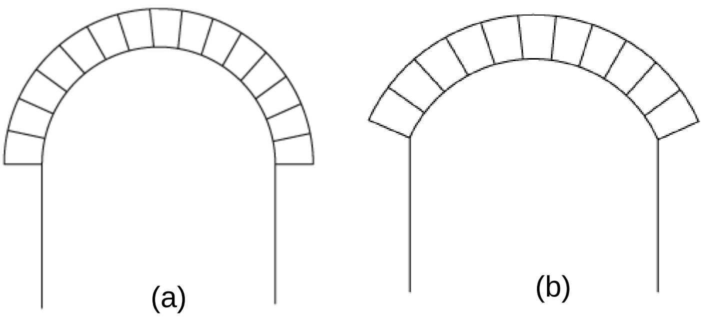


Figure 2.3: (a) semi-circular arch; (b) segmented arch (Roca, 2008)

The traditional Roman arches remained the main form of bridge construction for many centuries. However, advances in technology, and better understanding of the forces acting in an arch led to the use of different arch shapes in bridge construction. Many arch shapes that were developed were not used in bridge construction, however, because their shape did not improve the functionality of a bridge. For example, the lancet, or Gothic arch (Figure 2.4a), was developed in the 12th century and used in tall structures such as cathedrals where their narrow, high pointed shape was efficient in transferring forces to the foundations without large buttressing. This is not needed in a bridge, where the desirable shape is one that allows a long span, rather than a high rise.

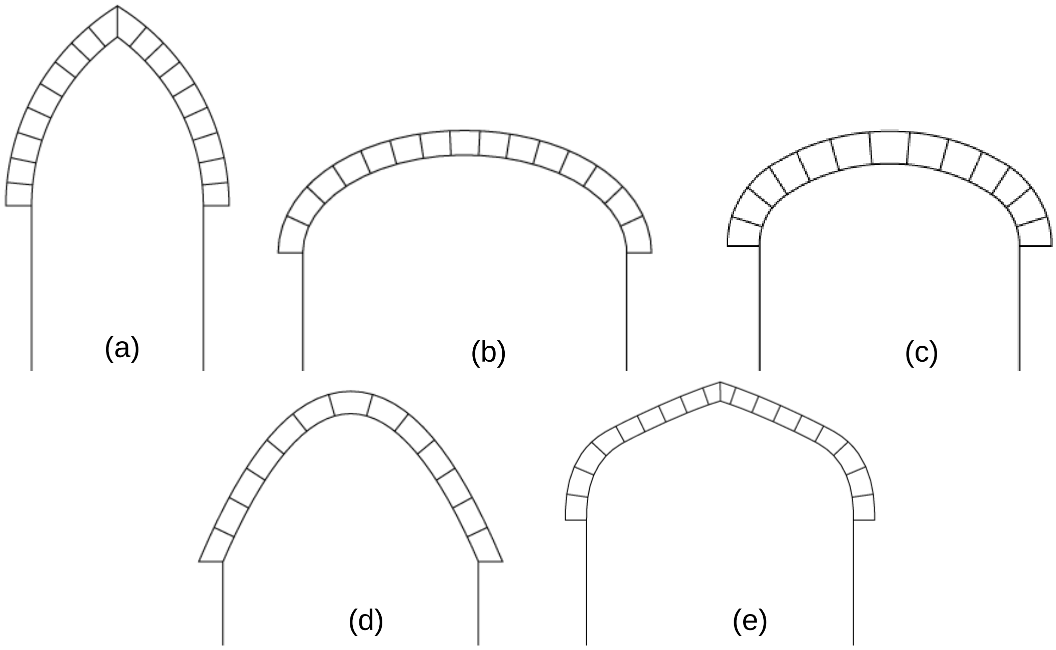


Figure 2.4: Common arch shapes in masonry brdges; (a) Lancet, or Gothic; (b)Elliptical; (c) Three-centered; (d) Catenary; (e); Tudor (Roca, 2008)

In the late 16th century, the construction of arch bridges entered a new stage of de velopment. New spans significantly exceeding those of the typical Roman circular arch were achieved. During the Renaissance, the circular and segment arch bridge were no longer the ideal designs. New, more efficient shapes were discovered by the works of scientists such as Galilei, Guidobaldo del Monte, Michelangelo, Alberti, Leonardo da Vinci, Palladio, and Fray Lorenzo. The three-centered curve, the elliptical and the catenary arch became the new forms (Figure 2.4). The three-centered arch has a curve composed of three different radii and centers. The catenary is in the shape of an inverted hanging chain, and was discovered to be the most natural thrust line for an ideal arch. These shapes and variations of them continued to be used in masonry arch bridges until the 18th century when new materials such as cast iron were developed.

2.2 Construction

The main difficulty in the construction of a masonry arch is the need for centering and/or formwork. This could often take the most consumption of material and work in the construction. One of the earliest ways of constructing an arch was to build up masonry and rumble underneath the intrados line and place the arch on top of the material. Then the material could be removed and let the arch set.

Another way of construction was to build scaffolding as a support during construction. These methods, however, consumed a lot of material and were often not feasible for bridges because many are built across running water ways or over crevices. Thus, the Romans developed a way to reduce the amount of formwork needed and the need for mid-span supports by supporting wooden formwork on the arch piers (Figure 2.5). The wooden frame supports both spans of the arch ring until they meet in the middle and the keystone is set in place. Furthermore, the Romans built a limited number of arch rings at once, thus reducing the size and capacity demand of the formwork.

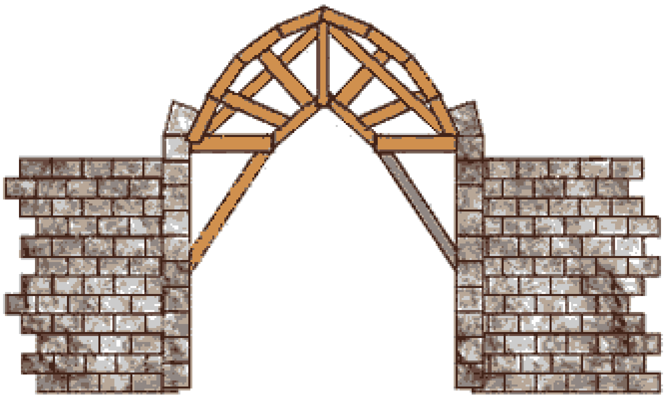


Figure 2.5: Wooden formwork supported on arch piers for the construction of masonry arches. (Norman)

Once the arch ring was set and often before removing the framework, typical masonry construction is used to build the parapets and then arch backing and fill is placed to provide more stability to the arch. Backing typically consists of resisting material (masonry or concrete) providing additional resisting volume to the arch ring. Fill usually consists of non-resistant material (often non-cohesive) meant to provide stabilizing, distribution of weight and some lateral confinement. A diaphragmatic arch has its spandrels fully composed of resistant material. Finally, the road surface can be placed on the fill.

The typical terminology for a masonry arch bridge is shown in Figures 2.6 and 2.7 below.

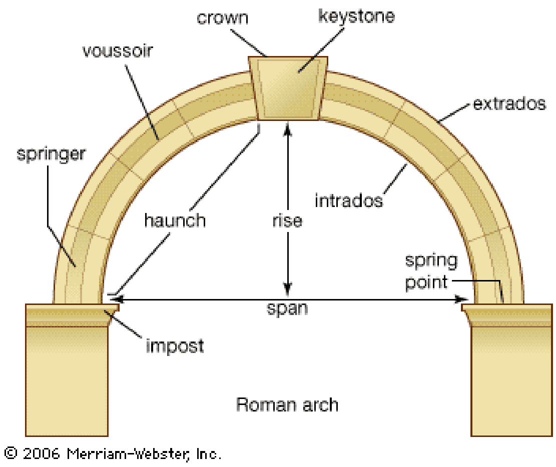


Figure 2.6: Typical terminology of an arch

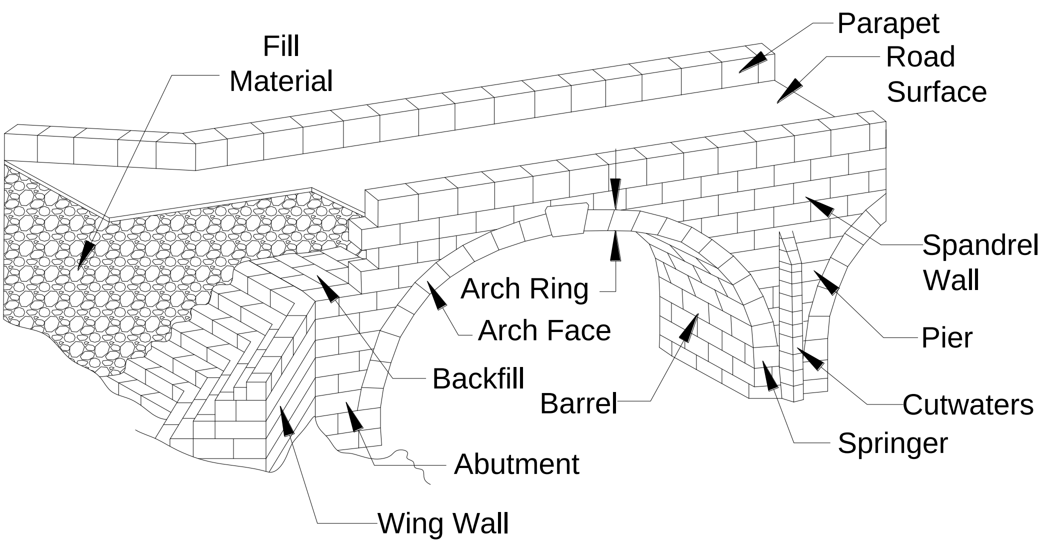


Figure 2.7: Typical terminology for masonry arch bridges.

2.3 Masonry Arch Capacity & Theories

The arch is the main load resisting element in a masonry arch bridge and therefore the most important element. The strength of masonry arches and vaults is highly dependent on their geometry and support conditions. The strength of the material normally is a secondary influence. The arch essentially works in compression, made possible by the horizontal reactions at the abutments which produce a normal force throughout the arch. In order to ensure the acceptable behavior of the arch, this force must be centered as close as possible to the center of gravity of the arch cross-section.

Bending moments produced by the eccentricity of the normal force must be considered as a parasitic effect on arch behavior (Favre, 2001).

Through the history of the arch, criteria allowing accurate design (shape, dimensions) of arches and vaults have been sought after. The strength and capacity ideas of the past were simply geometrical rules determined by the experience and the observation of past successful structures. Only in the 20th century have scientists determined a rational and general theory for masonry arches. However, today's theory for masonry arches is derived from ancient practices and rules and thus these early empirical criteria are still worthwhile and can be successfully used, in conjunction with more modern and sophisticated approaches, to assess historical masonry structures (Roca, 2008).

The early theories of arch capacities were based exclusively on experience and were set as proportions between different structural elements. By the mid 17th century, scientists realized the need for more rational principles. Sir Christopher Wren (architect of St. Paul Cathedral in London) considered the equilibrium of the moments caused by the weight in half of the arch. This was not correct, as it neglected the horizontal thrust of the arch. Other ideas were proposed and experimented with, however, they were also found inadequate. In 1675, Robert Hooke proposed the solution for equilibrium of an arch by means of an anagram (Figure 2.8). The solution (that of an inverted chain as the shape of equilibrium) was not deciphered until after his death in 1703.

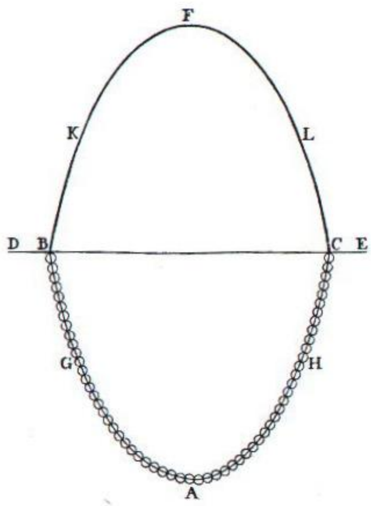


Figure 2.8: Robert Hooke's anagram pertaining to the solution of the equilibrium in an arch. (Roca, 2008)

The graphically oriented procedure became the main focus of masonry arch theory in the 18th century. The method divides the arch into a series of voussoirs separated by a series of planes. The thrust line is the resulting force of the sectional forces between each voussoir division across the arch (Figure 2.9). The arch is assumed stable if this thrust line remains within the boundaries of the arch.

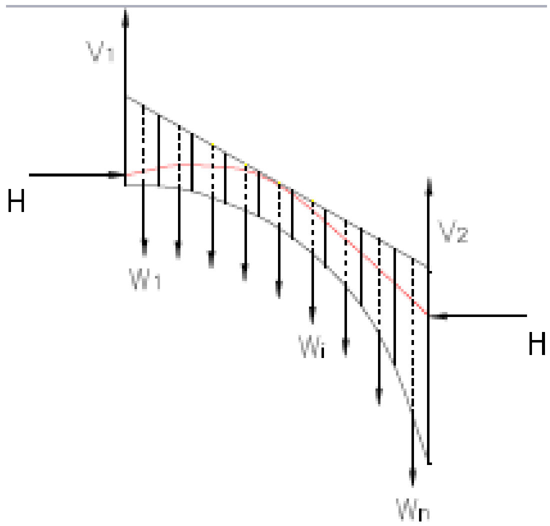


Figure 2.9: Division of an arch for graphical statics with thrust line (red). (Roca, 2008)

Furthermore, to start the calculation of the thrust line, it is necessary to assume a thrust force value, its position and its direction at one end of the arch. There are three variables in an arch (value, direction and force of thrust line) and each combination will generate a different thrust line; there are in essence infinite thrust lines. Thus, a problem exists that although finding one thrust line which is contained within the arch shows it is stable in that case, the arch does not necessarily act according to the chosen parameters.

In 1730, Couplet proposed that an arch collapses upon the development of a number of hinges, which causes the arch to become a mechanism. He also disregarded sliding between the voussoirs and assumed the hinges would appear at the base of the buttresses, in the center and at 45° (Roca, 2008). This proposal was confirmed to the degree of experiments available during this time.

In 1773, Coulomb proposed the first general and accurate theory about the stability of masonry arches. His basic assumptions were:

(1) Sliding between voussoirs is unlikely due to the existing frictional forces.
(2) Collapse will be caused by the rotation between parts due to the appearance of a number of hinges. The location of the hinges is a priori unknown but can be determined by the method of “maxima and minima”.

Following this proposal, scientists developed a theory called the “Middle-Third Rule”, which was arrived at on the basis that simple elastic theory will be observed. Also, it is assumed that the tension must be prevented. To keep the section in compression, the resultant force must stay within the middle third of the entire section. If the line of thrust protrudes outside the middle third, the development of tension will occur in part of the section (Figure 2.10d). Relating to the assumptions that masonry has no tensile capacity, this means the section would not be effective or actively contributing. This notion can be important to relate the position of the thrust line to cracks and the formation of hinges.

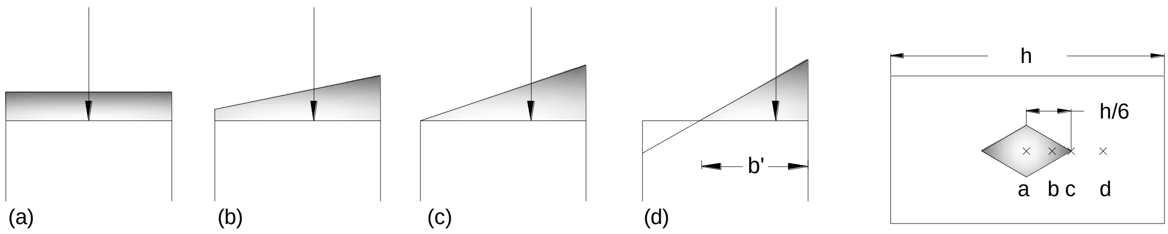
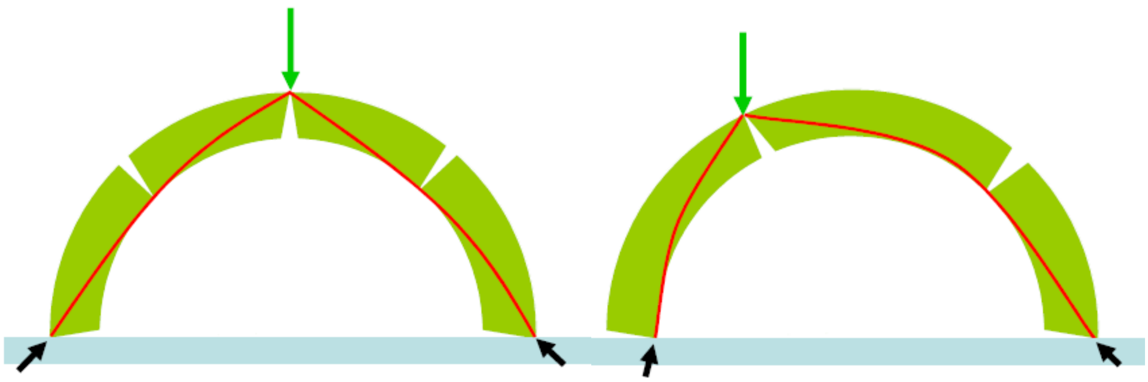


Figure 2.10: Stress distributions as the thrust line moves outside the middle third of the cross-section.

In the 19th century, rules of an empirical nature were meant to establish the structural form of the bridge, allow a first theoretical analysis to be carried out and provide an answer to the questions that arose most frequently regarding the stability of masonry arches. Most scientists did not take into account the strength of materials, the weight of the arch and the weight of superstructure live loads but, based on their conclusions on careful observation.

Although some theories relating to the thrust lines had been determined inaccurate, it was noticed that they are still an important concept. The thrust line will correspond with the location of a hinge. When the line of thrust becomes tangent to an alternate boundary, a hinge will develop at that location. It was determined that an arch needs a minimum of 4 hinges to create a mechanism. Some typical collapse mechanisms are shown in Figure 2.11.



(a) (b)

Figure 2.11: Collapse mechanisms with a possible corresponding thrust line (Roca, 2008).
(a) Typical 5-hinge collapse mechanism of an arch with symmetrical loading and geometry;
(b) Typical 4-hinge collapse mechanism of an arch with asymmetrical loading and/or geometry.

Using the ideas of collapse mechanisms and thrust lines, several ideas of identifying the capacities and limit states were proposed. The attention was directed towards finding the actual thrust line among the infinite solutions which can be drawn in a stable arch. The theory of the thrust line, however, was a tragicomedy of unsuccessful attempts to remove the static indeterminacy by means of empirical hypotheses or metaphysical principles (Ageno, 2004).

Not until 1966 with Jacques Heyman's work did an appropriate limit analysis appear. He introduced a formulation that was based on the plasticity theory rather than the inadequate elastic theory. His analysis is under the assumption of the following three hypotheses:

(1) Masonry has null tensile stress
(2) The compression strength of the material is infinite
(3) Sliding between stone blocks is impossible

Failure is due to the generation of a plastic mechanism.

Heyman stated an upper and lower (safe) bound theorem within his hypotheses. The lower-bound theorem states that if a thrust line can be found, for the complete arch, which is in equilibrium with the external loading (including self-weight), and which lies everywhere within the masonry of the arch ting, then the arch is safe (Heyman, 1966). The important part of this is that the thrust line need not be the actual thrust line. Thus, finding one satisfactory thrust line, it can be known that the arch cannot collapse and the need to examine failure modes is not required.

The upper bound theorem states that under an assumed mechanism (arbitrarily providing sufficient number of hinges), equating the work of the external forces to zero will result in a load which is and upper-bound estimation of the actual ultimate load. The theory solves for the point at which the structure will fail, providing an upper approximation of its capacity.

Furthermore, the uniqueness theorem provides an additional limit condition if a statically and cinematically admissible collapsing mechanism can be found. In other words, collapse will happen if a thrust line which causes the necessary number of plastic hinges to develop a mechanism. The resulting load is the true ultimate load with a corresponding ultimate mechanism and thrust line. In addition, a minimum and maximum thrust necessary for arch stability can be determined by positioning the reactions in the appropriate locations as seen in Figure 2.12.

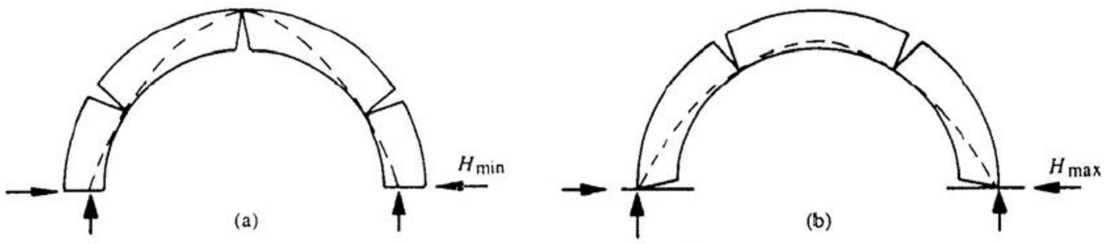


Figure 2.12: Semicircular arch under self weight; (a) Minimum thrust and (b) Maximum thrust by applying uniqueness theorem. (Heyman, 1995)

As seen above, some of the ancient and early empirical criteria are still worthwhile for the assessment of masonry arches. Additionally, the geometrical rules can contribute to simple analysis such as to verify whether the structure was consistently designed according to contemporary criteria and gain a first and quick insight on the adequacy of the design and safety condition. Limit analysis depicts realistically the collapse and capacity of masonry arches. In combination with other tools, it can be a very reliable analysis.

Many additions to the theory have been studied and experimented, however this remains the fundamental principle behind them. More recently, numerical approximations and software analysis have been developed. As the focus of this paper is not the assessment of masonry arch bridges, these additions and more detailed descriptions of the above, will not be discussed. Appendix A provides a list of some available resources on the assessment of masonry arch bridges.

3. MASONRY PROPERTIES

Masonry is an assemblage of stones or bricks with or without mortar between the joints. The mechanical and physical properties of masonry will vary between different bridges. There may be similar behaviors, but the values at which certain behaviors occur will be different. Differences result from the type of brick, stone and mortar used in the construction of the particular bridge. While modern masonry units are manufactured by machines and provide uniform properties, the production of historical units was not always consistent. Also, the minimal knowledge of mortars caused a wide variety of properties.

In any case, it can be said that mortar adds little strength and tensile forces cannot be passed from one part of the structure to another (Heyman, 1998). An important property of masonry for arch bridge is its high compressive strength, as the stability of an arch depends on constant compression in the ring. The compressive stresses in even a large bridge are typically low when compared to the limiting strength of the material. The usual assumptions made of masonry for arch bridges are that:

1. It has no tensile strength
2. It has virtually infinite compressive strength
3. Slip does not occur between components of the structure.

These assumptions allow the issue of unknown values for properties to be brought within the framework of plasticity theory and a clear analysis of the arch to be made.

Generally, these assumptions prevent the need to determine exact values of the properties for the means of capacity analysis. Where further properties may be important are in the design of a compatible intervention. It is necessary when replacing or introducing new masonry to an existing bridge that the properties are compatible. For instance, introduction of brick, stone, or masonry that have higher strength properties can cause local stresses which can be damaging to the surrounding material and lead to more damage. On the other hand, mortar added with low strength values compared with the existing mortar will usually deteriorate under the applied forces and not properly transmit forces across joints.

Chemical properties of stone, brick and mortar are sometimes important. The addition of material with differing chemical properties may result in unfavorable bonds or reactions with the existing material. Damages to the strength, stability or appearance are possible.

Many tests, both destructive and non-destructive, are available to help identify material properties when necessary. These will be discussed in the following chapter.

4. DAMAGES AND FAILURES

Masonry arch bridges exhibit a wide variety of deteriorations, damages, and failure from natural or man-made effects. During inspection and assessment of a bridge for conservation, the possibility of multiple damages and failures in the same bridge is appropriate. Causes of damages and failures can be a result of construction techniques, long-term loading, over loading, transient loading or environmental factors. Compiled in the following sections are common causes and types of damages and failures found in masonry arch bridges.

4.1 Support settlements

When piers or abutments settle, typically large cracks will occur on the span of the arch and movements throughout the structure. Settlements and the causes of settlements are often dramatic and can be seen upon visual inspection. Some reasons for damages due to support settlements include:

1) Exceeding of bearing capacity of soils under the supports. As many bridges were built before a knowledgeable understanding of soil mechanics, it is common to find settlements due to unfavorable soil conditions. Many times builders would place timber piles under the foundation of the bridge to prevent settlement. However, in some cases these piles may rot and become ineffective or the modern loads just exceed the effective resistance of the piles.
2) Consolidation of subsoils, shrinkage of underlying clays and the presence of expansive soils may be responsible.
3) A change in moisture content or water table level, possibly caused by a burst water main or the presence of tree roots.
4) Sand and gravels near the foot of the pier are sometimes removed by people for other uses. This opens vacancies around the base and provides less support to the piers and abutments, allowing the possibility of settlements.
5) Material deterioration. Timber piles or the masonry work may decay leading to a weaker foundation prone to settlement.

Figure 4.1: Example of failure from support settlement on Mataraci Bridge in Turkey (Ural, 2007).

4.2 Scour

Scour of foundations is one of the most common causes of damage and failure in masonry arch bridges in waterways. Scour is the erosion of the stream bed around and from under the foundations of a bridge. Results of scoring can cause severe settlements and/or movements in the bridge, leading to development of hinges and possible collapse. It may be difficult to detect in earlier stages because it is likely to be at its worst when the river is in flood conditions and the access to the underwater foundations is impossible. Scour holes may then fill in when floods subside disguising any undercutting of the foundation.

River bed levels may drop during floods as the water carries away the bed material. In fact, a bridge across the waterway may cause additional local lowering of the bed level. The extra erosion may occur first from an increase in flow velocity due to piers constricting the channel; this is usually referred to as general scour. Second, the piers and abutments cause a local disturbance of flow (turbulence) which causes additional erosion and is called local scour. The total affect of scour on the bridge will result from the combination of both types.

To further explain, water flow is normally parallel to the river bed and an obstruction such as a bridge pier, changes the direction of flow around the pier. A downward flow occurs on the pier face and a reversal of flow along the river bed in front of the pier. This flow produces a horseshoe vortex (named after its plan shape) which extends around the sides of the pier (Figure 4.2). Also a wake region at the rear of the pier (downstream side) will develop with vortices being given off in intervals. The shape of the pier will affect the horseshoe vortex and wake region. Streamlining of the pier (sometimes called cutwaters) at the upstream and downstream ends will have a beneficial effect, creating less turbulent flow, similar to the aerodynamics of an airplane wing. The cutwater must be parallel with the flow to provide the most benefits and can become ineffective if directions of flow are changed for any reason. Some equipment has been developed to automatically detect the presence of scour. This should be used to assist the choice of intervention.

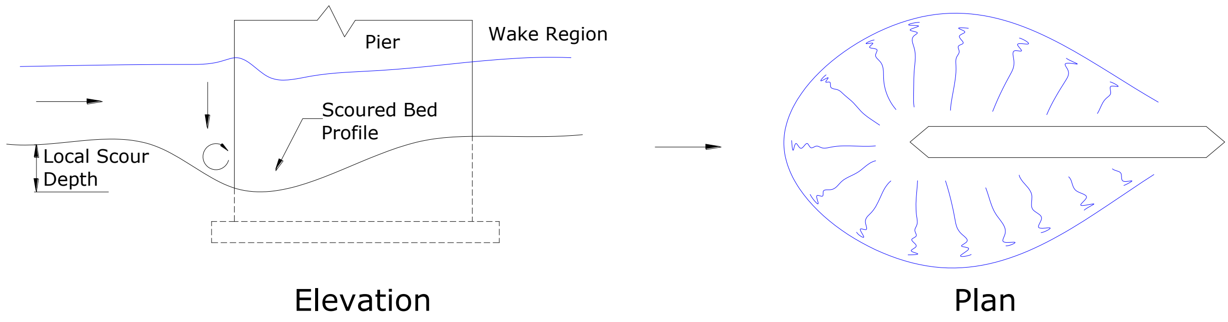


Figure 4.2: Scour of foundations

4.3 Floods

In areas of frequent flooding or where large floods have been reported, damage to bridges is almost certain. During floods, large lateral forces are subjected to bridge from the hydrodynamic pressures as well as large objects such as trees the water may be carrying. These forces, particularly impact forces, can cause much damage to the structure. Stones or bricks may be broken off from the bridge and mortar eroded away. As mentioned previous, stream bed and surrounding banks will also experience eroding which can lead to instability. Floods can be a devastating event for a bridge to experience.

4.4 Earthquakes

The damages due to earthquakes typically occur on the mid-span of the main arches as cracking and the separation of the roadway. Stone and other such materials are strong in compression and somewhat so in shear, but cannot resist much force in tension as thus the masonry arch bridge is designed to be constantly under compression. However, an earthquake will not only introduce vertical loading but also lateral loads and tensile stresses. Consequently, lateral displacements, cracking and lose of masonry units may occur and cause damage. Earthquakes are not a leading cause of damages in masonry arch bridges, but should be considered.

4.5 Insufficient Coverings and Drainage

Improper covering and drainage systems may affect the bridge in several aspects. If coverings and drainage systems do not work, rainwater will penetrate and remain inside the bridge. The water will not cause immediate affects to the load capacity, but several long term affects can occur which may eventually lead to a decrease in load capacity. Damages which may result are: (1) wash out of fines located in the fill or mortar between joints, (2) allow freeze-thaw cracking and damages, (3) lead to corroding of metal parts in the bridge or (4) deteriorate masonry units through crystallization.

4.6 Deterioration of Masonry Materials

If masonry materials have poor performance against environmental conditions, they will deteriorate and cause damages to the bridge. These damages usually take place over a prolonged period of time. Deterioration may also be induced by loading affects, such as crushing. Weak masonry can lead to cracking, settlements, movements or even the development of hinges.

Figure 4.3: Deterioration of masonry material (Ural, 2007).

4.7 Increased Loading

Bridge loads have certainly increased over the past centuries in both weight and frequency. The differences in loading are typically not the loads the original builders designed the bridge for. If the bridge does not have sufficient strength to resist the vertical loads and resulting horizontal thrusts, structural damage will occur possibly in the form of cracking or even the development of hinges and a mechanism.

4.8 Wars

As bridges are important transportation links, they are main targets in an effort to cripple or prevent advancement of enemy forces. At times of war, the importance of cultural heritage seems to be forgotten and many bridges of significance are destroyed. Usually, the entire bridge or main span of the bridge is completely collapsed.

4.9 Vegetation

Without regular maintenance, vegetation can grow in the bridge. Vegetation can affect both the appearance and stability of the bridge. Particularly heavy rooted plants will cause contractions within the masonry, leading to cracking and further damages. If vegetation has the opportunity to grow large, removal of vegetation can be dangerous itself, as roots may be now holding together portions of masonry or filling voids that may otherwise collapse.

4.10 Splitting Beneath Spandrel Walls

Spandrel walls stiffen the arch ring at its edges. Flexing of the arch ring due to traffic loads and outward movements of the spandrel will produce shear stresses between the outer edge of the ring which is stiffened by the above spandrel wall and the barrel which only contains flexible fill above it. Figure 4.4 shows a severe example of the cracking and separation that can occur. When the bridge contains stone spandrel walls and external voussoirs with the remaining arch made of brick, this is particularly vulnerable to such failure. Water may lend assistance to this type of damage if it penetrates to the spandrel wall and arch interface and deteriorates the mortar. Outward forces on the spandrel wall due to the fill may lend further assistance.

Figure 4.4: Longitudinal crack in arch ring (Page, 1996).

4.11 Damages from Abutment Movements

Abutments can be subjected to forces that move them outwards or inwards; the arch generates outward horizontal thrust and the fill behind abutments generate inward forces. The effects of movement s on the arch depend on which direction it moves and whether there is rotation of the abutments. Transverse cracks in the arch ring are likely to manifest. If only one end of the abutment settles, longitudinal cracks are probable (Figure 4.5). This can become particularly serious if the arch ring is divided into independent segments by the cracks. Diagonal cracks may occur when one abutment tilts relative to the adjacent one. The crack will typically start at a springing near one side of the arch and propagate towards the center of the crown.

Figure 4.5: Longitudinal cracking (Oliveira, 2004)

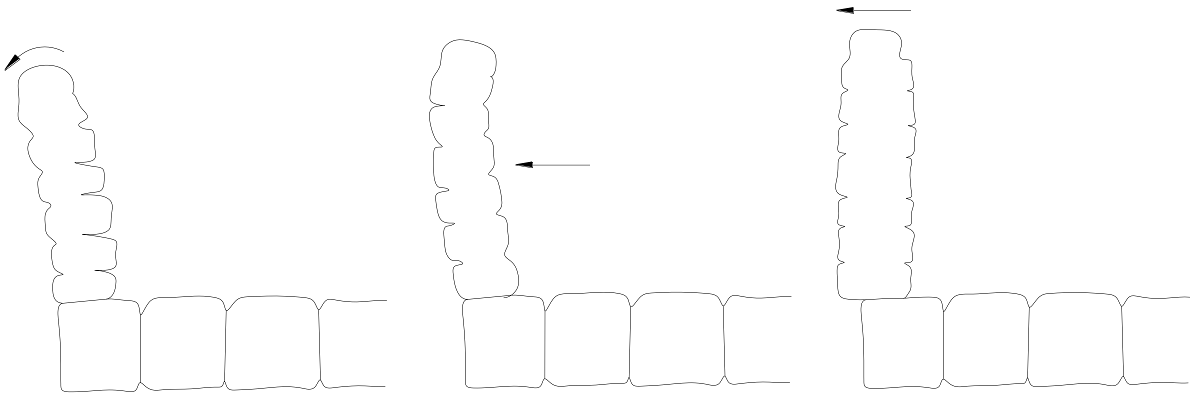
4.12 Ring Separation

Multi-ring brick arches commonly experience separation between rings. This may occur due to chemical deterioration of mortar or it may be load induced. Separation between mulit-ring arches will reduce the total effective ring thickness in the arch. The arch ring may also separate at the interface of the spandrel wall. Tests have shown that this can significantly affect the load capacity of the bridge.

4.13 Spandrel Walls

Spandrel walls are a big maintenance problem with masonry arch bridges. They experience the same deterioration threats normally associated with exposed masonry, such as weathering and loss of pointing. They are also affected by dead and live load lateral forces such as those generated by the fill or vehicular impact on the parapet or freeze-thaw cycles of the fill. Outward movements typically occur because of live load forces compressing the fill and causing it to push out the spandrel. A longitudinal crack at the connection between the road surface and spandrel wall will permit debris to enter which will prevent any possibility of the crack closing, and also permit water to enter the structure which may then freeze in winter.

The effects on the spandrel walls may be outward rotation, sliding on the arch ring, or bulging (Figure 4.6). Typically the outward forces are not enough to inhibit cracking of the arch ring, but in conjunction with flexing of the ring, this failure is more probable.



(a) (b) (c)

Figure 4.6: Outward Spandrel Wall Movements; (a) Rotation or tilting (b) Bulging (c) Sliding

4.14 Wing Walls

Wing walls may be damaged similarly as spandrel walls. They are more likely to see affects from movements in foundations than spandrel walls. Lateral forces may be of bigger concern as wing walls are higher than spandrel walls. Vegetation growth and blocked drainage are common around wing walls.

4.15 Parapets

Parapet deterioration is often in correlation with movements in the spandrel or wing wall. They may also be struck by traffic. Tests have shown that irrespective of mortar strength, parapets of at least 400mm thickness and 10m in length can resist the impact of a 1.5 ton vehicle traveling at 100 kph, impacting at a 20° angle (County Surveyors' Society, 1995). Thus it is believed that most masonry parapets are not in need of upgrading for current traffic loads. However, an impact is likely to cause damage to the parapet and spandrel wall which will require replacing.

5. INVESTIGATION AND TESTING

An critical part of any intervention is to first understanding the structure; how it was built, materials it was built from, geometry of the bridge, properties of materials, condition of the materials, past interventions, structural behavior and loading conditions. The first task in understanding the bridge is to research any past documents, photos, inspections, drawings, and the like. Next, a physical inspection of the bridge should be done on site, and possibly non-destructive testing. Often, conservative material properties are assumed for the masonry and further material testing is unnecessary. It is necessary to keep in mind that material properties are likely to be variable throughout the bridge and many locations and samples would be needed to provide statistically valid values. In addition, some tests may damage the stability or appearance of the bridge, in effect causing additional repair work.

Visual inspection is the first investigation that should be done. During this examination, items that should be noticed and recorded are cracks, spalling, displacements, staining, bulging, missing mortar, and other signs of damage. In addition, accurate dimensional data for the bridge is important for assessment and then design and construction of the intervention. Particularly the shape of the arch ring is important for determining load capacity. During visual inspection, non-destructive testing such as hammer tapping or scratching of mortars may provide valuable information on the condition of the structure. Parapet, wing and spandrel walls, piers, abutments, fill and road surface should also be visually inspected and not just the arch.

After visual inspection, if further material properties are needed, non-destructive tests may be used. Just as it is important to provide an intervention which respects the cultural value of the structure, it is also important to apply this to testing techniques. Therefore, the least destructive methods are preferable in the testing of historic structures.

A wide variety of instruments and techniques have been developed to test historic masonry structures. The objectives of these tests are to further characterize the materials, identify decay and damage, determine the stability of the structure and to identity any environmental effects on the structure. Any test which visually affects the structure should be covered after the test in a way that does not detract the appearance of the structure.

5.1 Non-destructive Testing

<u>Rebound Hammer</u>

A rebound hammer involves tapping a hammer with consistent force and interpreting the sound and rebound of the hammer. It can be used to detect separations or large voids near the surface and uniformity. It is simple to use and inexpensive, however it has no direct relationship to strength or deformation.

<u>Load Testing</u>

Load testing is simply applying test loads to the bridge to determine if it has adequate capacity. This is typically done with vehicles. A lighter vehicle is first loaded on the bridge followed by an increase in the number of vehicles or the tonnage of the vehicle. Observations are made and any noticeable deformations revealed damages are reported.

<u>Sampling and Coring</u>

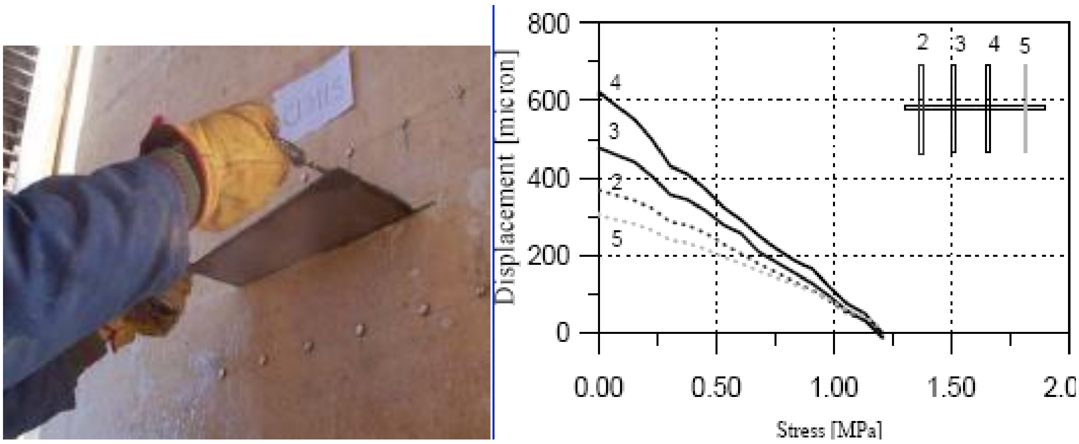
Sampling and coring is helpful in understanding the morphology of the masonry. Sometimes a few bricks or stones can be removed and the inner of the structure can be surveyed photographically and the section of the wall can be drawn (Figure 5.1). However, if this does not provide acceptable results or is undesirable for other reasons, coring may be done. This is beneficial as it can be done through the full section of the bridge to understand the condition of the inner section. Coring is done by drilling out a core of material. Once the typology has been mapped using the core sample, the core may also be used for samples to test material properties in the laboratory. This is particularly useful for determining the type of mortar and fill materials that are in the bridge. If appropriate, the drilled hole may also be used in the case of anchoring interventions, to allow for minimal disruption to the structure.

a) b) c)

Figure 5.1: Drawing of wall section: a) left face of section, b) photo of the excavation, c) right face of the section. (Binda, 2009)

<u>Flat Jack</u>

Flat jack tests allow for a good approximation of the state of stress and stress-strain behavior of the masonry. A perpendicular cut is made in the masonry and allowed to close. Displacements in the top and bottom of the cut are measured. A thin flat-jack is placed inside the cut and the pressure is gradually increased to obtain the distance measured before the cut. The displacement cause by the slot and the ones subsequently induced by the flat-jack are measured by a removable extensometer. With the values of displacements and pressure applied to regain the original position, the stress value can be determined.



a) b)

Figure 5.2: a) Placing flat jack; b) Results of single flat-jack test (Binda, 2009)

The test can also be used to determine the deformability characteristics of masonry; this is called a double flat-jack test. A second cut is made parallel to the first one and a second jack is inserted. The two jacks in a sense isolate a masonry sample of appreciable size to which a uni-axial compression stress can be applied. The test gives a good approximation of the stress-strain behavior (Figure 5.3).

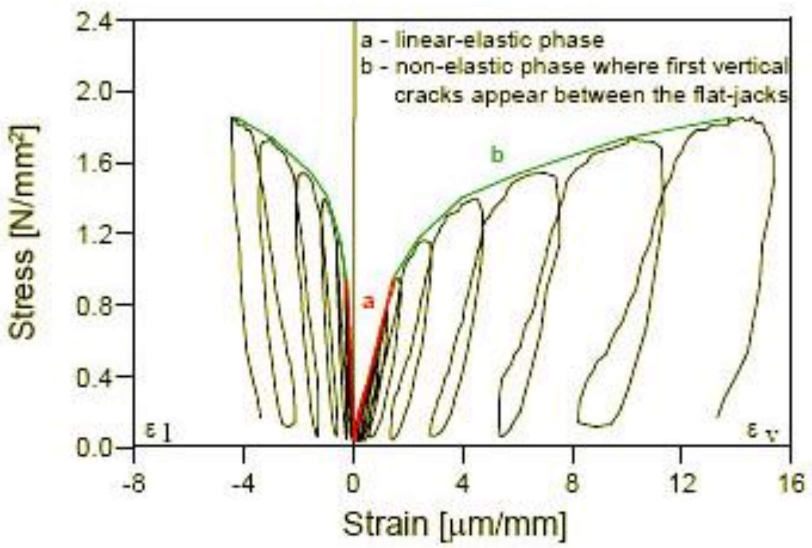


Figure 5.3: Double flat-jack test; stress-strain behavior (Binda, 2009).

It is important to determine a reliable value of pressure to gain accurate results from these tests. For the double flat-jack test, difficulties or failure in the determination of the stress-strain characteristics may be found if there is low stress acting above the jack. Therefore, the double flat-jack test is not always available for testing of bridges.

Ultrasonic Pulse Velocity Test

Using ultrasonic waves, the travel time for a known distance is recorded to give a measure of the density of the material, which can be related through calibration to strength. High frequency waves (20 to 100 kHz) are used for short path lengths in relatively sound masonry, whereas lower frequencies (1 to 10 kHz) are used in old or damaged masonry with high attenuation properties. Longer travel times (that is, lower velocities) can indicate the presence of voids (Hamid, 2009).

Radar Test

The radar testing technique uses high-frequency electromagnetic waves (100 MHz - GHz) emitted through an antenna with very short impulses and allows determination of possible separated surfaces between materials. The test can be used in any type of masonry and can emit at long distances. It can be used to establish uniformity, detect flaws and delaminations, and the thickness. It only requires access to one surface. However, the test seems to have no direct correlation with the properties, the wave analysis is complicated and the process is expensive.

Infra-Red Thermography

Thermal imaging cameras are used to record variations of temperatures and display ranges of temperature as different colors. It can be used to detect uniformity, flaws, embedded structural elements, or voids. It is a simple and quick method. Results are affected by weather conditions and moisture.

Strain gauges

Strain gauges may be used to measure long term changes in strain or the growth of cracks. They require the gauge to remain attached to the surface and can detract from the appearance of the bridge.

5.2 Destructive Testing

Destructive testing is not preferable to use, as it will destroy part of the structure. However, there may be a rare case in which it is necessary, as this is the only way of estimating the true strength of the old masonry. These tests require parts of the structure to be removed, maintaining the integrity of the sample, and tested in a laboratory. Many tests may be carried out to determine every necessary property. Mechanical properties such as compressive strength, tensile strength, modulus of elasticity, and shear strength may be determined. As destructive testing for masonry bridges is very rare, these tests will not be discussed in detail.

6. REPAIRING AND STRENGTHENING TECHNIQUES

6.1 Introduction

The development of a variety of strengthening and repairing techniques has been necessary for the many differences among historical masonry bridges. Particularly the many causes of degradation, different failures, and needs for upgrading load-bearing capacity must be considered in defining the conservation works needed for a bridge. Presented is a discussion of common techniques which have proved to be useful in one or multiple aspects of damages and faults. This report does not serve as a design manual or as requirements for masonry bridge repair. Rather it should exist to inform engineers and those working with masonry arch bridge conservation of the available methods. Each discussion will provide general information of the following:

- Repair Location (arch ring, spandrel wall, infill, or others)
- Materials used in intervention
- Basic design considerations
- Basic construction methods
- Advantages and disadvantages
- How the intervention affects the appearance of the bridge

As costs are also an important point in conservation works, many of the intervention techniques will include a brief note on costs. However, as costs have many variables in masonry arch bridge conservation, such as the location of the bridges, the sizes of the bridges (spans, rises, width, area, and volume), the original materials, and other individual issues for each project, a detailed description of costs is not feasible. Instead, an attempt at a general comparison of costs between techniques is used to provide considerations for the choice of intervention.

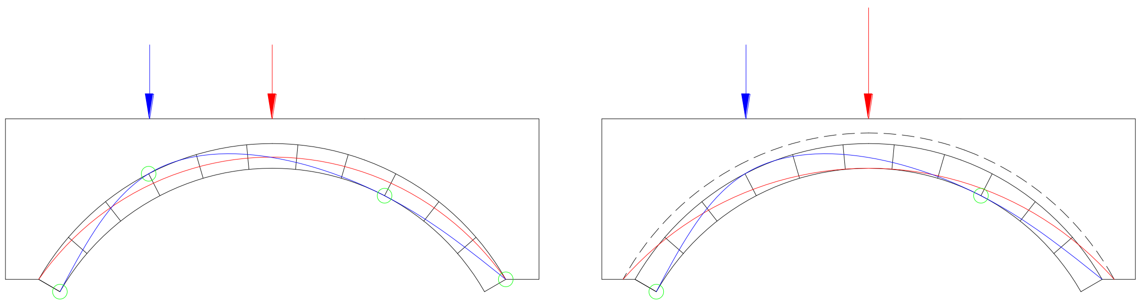
Each discussion also includes a note on traffic and services disruptions. Traffic refers to both pedestrian and vehicular movement across the surface of the bridge as well as any waterway or vehicular traffic beneath the bridge. The movement of traffic across the bridge is the main function of a bridge and should be disrupted minimally. A secondary function of bridges is to carry services. That is, any water, waste, mechanical or electrical lines that may run through the bridge. These may be embedded in the fill or run along the side of a bridge. The locations of these services should be determined before any intervention proceeds.

6.2 Principles of Strengthening Masonry Arch Bridges

The main structural element of a masonry arch bridge is the arch and thus many strengthening techniques are based around stabilizing and improving the performance of the arch. In considering the way an arch behaves statically and under loads, there are several principles which will be of use when designing a strengthening intervention. These principles reflect the geometric theories that scientists have experimented with for several centuries. The main idea is that the geometric form must be one that forces the structure to be subjected predominantly to compressive forces and allows an appropriate path for the line of thrust. Deformations and tensile forces should be limited.

The first consideration is the arch ring thickness. In increasing the thickness of the arch, the cross-section for which the thrust line must be contained is also increased. An arch which has developed hinges due to the thrust line becoming tangent to the perimeter of the existing arch ring may be restored by increasing the thickness of the ring by an appropriate amount. The load applied at approximately one-fourth of the span (blue) in Figure 6.1a has caused the development of hinges (green circles). In Figure 6.1b, the increased arch ring thickness restores the integrity of the arch by removing two hinges, simply by allowing the line of thrust to remain inside the geometry of the arch. If a bridge has shown noticeable deformations or collapse, perhaps due to the development of a mechanism, strengthening and repairing is more than just a geometrical consideration and other improvements are necessary.

Increasing the arch ring thickness also allows the load capacity to increase, as the line of thrust has a wider section to "move" within the containment of the arch when live loads are applied to the bridge. In Figure 6.1a, the load at mid-span (red) is a limit state for the arch. A larger load will force the line of thrust outside the thickness of the arch at the springers. By increasing the thickness of the arch in Figure 6.1b, it is seen that a larger load may be applied before the line of thrust reaches the geometrical bounds of the arch ring.



(a) (b)

Figure 6.1: (a) Applied loads with possible lines of thrust; (b) Increased thickness of arch ring (dotted arch) and possible lines of thrust. Green circles represent hinges.

In addition to increasing the effective thickness by a physical material boundary, tensile resisting material can be used to provide a better eccentricity of the thrust line. The tensile forces allow the line of thrust to protrude outside of the physical geometry of the arch without causing a mechanism to develop. The tensile forces that would typically develop in the arch are transferred to the tensile resisting material and thus the load capacity is increased as the line of thrust can extend beyond the geometry of the arch.

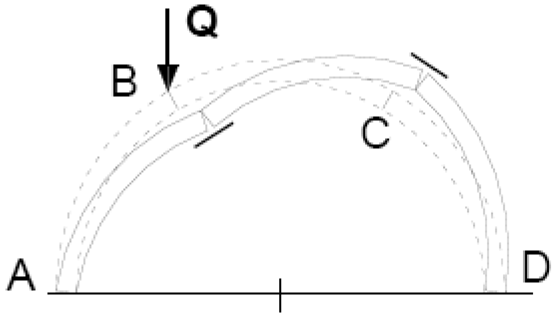


Figure 6.2: Cracking at tensed edges, where tensile material will carry the forces. (Valluzzi, 2001)

The next principle to take into account is increasing the weight of the abutments. This may be done by improving or adding to the backfill. The increase in weight will create a larger vertical force on the abutment where the forces from the arch are applied. By the principle of summing vectors, the increase in vertical force will alter the path of the thrust line to a more central (and thus more stable) location at the base of the abutment. Figure 6.3 demonstrates this principle, where in (a) the backfill is shallow and the resultant force (green) from the addition of the vertical abutment load (blue) and the line of thrust from the arch (red), is reacting towards the back of the abutment. The front of the abutment is not carrying any load, and the abutment is likely to rotate.

In (b), the backfill is increased provided the larger vertical load that shifts the reaction at the base of the pier to a more stable location. The geometrical figure of the summation of vectors is shown to by each case. Increasing abutment weight can help stabilize a bridge which has signs of rotating abutments or help increase the load capacity of any bridge by allowing greater horizontal thrusts to act on the abutment.

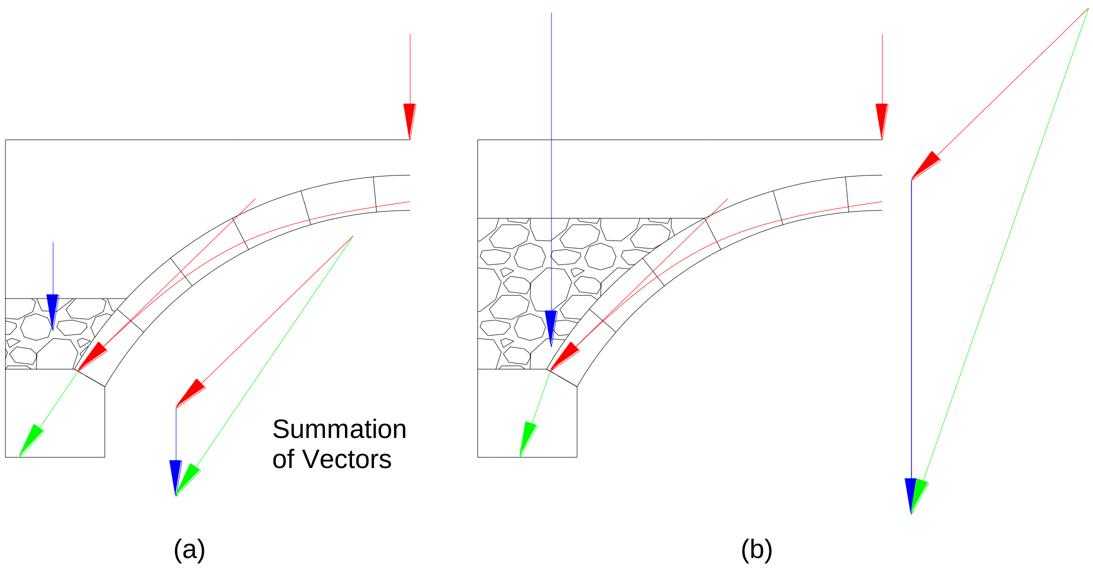


Figure 6.3: Location of abutment reactions under given loads with: (a) a shallow or deteriorated backfill, and (b) an improved backfill.

The next principle is from the effect of an increase in dead load over the arch. Increasing dead load provides more compression through the arch and a larger horizontal thrust. This improves the eccentricity of the thrust line within the arch ring and allows better performance of the bridge under live loads. Of course, there is a limit to the amount of dead load that can be added, in consideration with the capacity of the arch and the foundations.

Another principle focuses on the distribution of live loads across the arch. A uniformly distributed load creates a parabolic thrust line, which can more easily fit within the bounds of the arch ring (as opposed to an irregular curve). By adding a stiff continuous material, such as concrete, above the arch in a symmetrical way, capacity under live loads can be increased. First, the additional fill will increase compressive forces through the arch and reduce the introduction of tensile forces. This is good for the stability of the arch as compressive forces are how an arch maintains its strength. Second, the symmetric and uniform fill will distribute forces throughout the arch and prevent local effects of concentrated loads.

Last, the consideration of altering the path of live loads is interesting. Through interventions such as relieving slabs, the live loads can essentially be forced to be loaded on the abutments and/or crown of the arch (Figure 6.4). Loading on the abutments will have the same effect mentioned above for adding weight to an abutment, but rather uses the live load as the additional vertical load on the abutments. In a sense this increases the load capacity as live loads are applied. Alternatively, if more horizontal thrust is desired (because of inward tilted abutments, for example), then live load can be forced to act more on the crown of the arch.

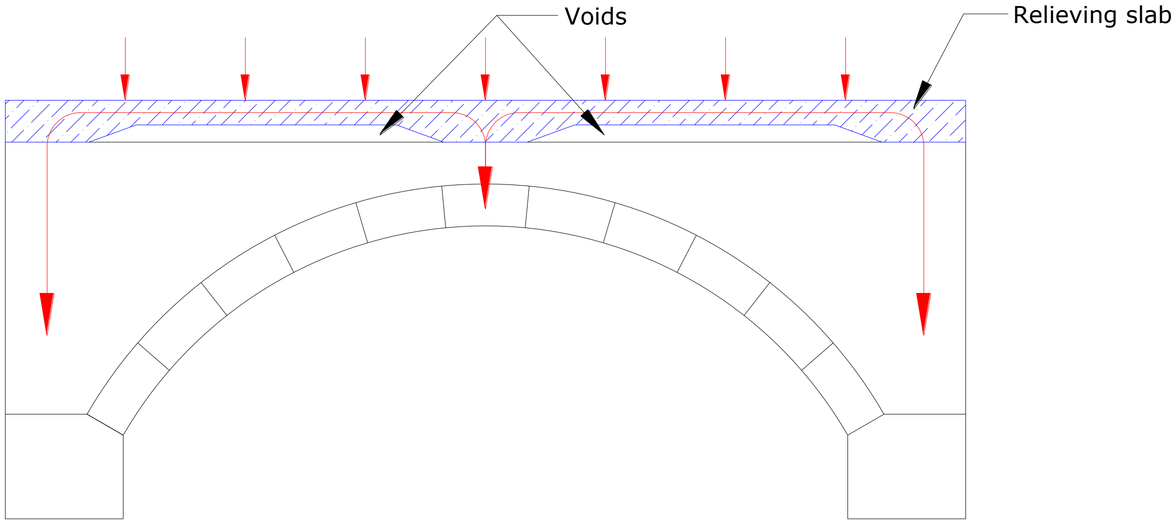


Figure 6.4: Using a relieving slab to alter live load paths to abutments and arch crown.

These are certainly not the only principles to consider in strengthening an arch, but are the common principles that simply follow geometrical rules by which many strengthening techniques are governed by.

6.3 Compatibility and Durability of Interventions

Interventions may use a variety of materials such as concrete, steel, epoxy resins, soils, mortars, stones, and bricks. With the introduction of these new materials to the historic structure, compatibility of these materials with each other and with the older materials must be considered both for the immediate future and for years to come. By compatibility, it is meant that the interaction between the materials and elements of the structure, whether chemical or physical, react properly with one another for the purpose of stability and appearance. Incompatibility may lead to local stresses, alteration of load paths, or over stiffening.

The materials introduced to the existing structure should also be applied in such a way that they remain compatible for a long period of time. The intervention must be durable to the environment, cyclic loading and fatigue. Not only the material itself must be durable, but the way in which it is applied in the structure must be durable. It is not economical to repair a bridge every four or five years due to an incompatible or non-durable intervention. A long life without further intervention should be a goal of repair and strengthening techniques. This must be considered in the design of the intervention.
Some general recommendations are as follows (CNR-DT 201/2004):

- Correct design of connections between materials, giving priority to the realization of the connections, taking into account the constitutive behavior of the materials used.
- Limit stresses in service conditions to ensure admissible stress states for all of the materials involved, taking into account temperature and humidity variations.
- Insurance of the effectiveness of the strengthening by adopting construction details that allow an easy protection of the added materials against the environmental and accidental factors thus avoiding the need to use additional protection materials.
- Protection of the elements against the environment is crucial to providing a durable intervention.
- Construction must be done with care and attention; one incorrect installation can compromise the entire structure.

6.4 Choice of Intervention

It is the responsibility of the engineer to analyze and determine the best method for intervention. Before a decision can made, the cause of any and all known deterioration must be understood. Then, an assessment of the entire bridge's stability must be done. The assessment should be done with the assistance of non-destructive or, if appropriate and necessary, destructive testing to determine material properties. Then, numerical analysis, modeling in computer software, and other similar methods should be used to determine capacity and stability of the bridge. Assessment of the effect a repair will have on the behavior of the existing structure should also be determined.

A variety of factors may influence the choice of strengthening or repairing methods other than just the type of deterioration the bridge has experienced. When selecting and designing a bridge intervention, it is necessary to consider whether the intervention can provide the following recommended requirements partly adopted from S. W. Garrity (Garrity, 2001):

a) Respect the authenticity of the bridge. Both the materials used and the appearance should remain as similar to the original bridge as possible. Aesthetic appeal should be maintained or improved.
b) Increase load-bearing capacity. A consideration of all parts of the bridge and their ability to resist the appropriate loads.
c) Provide a compatible and durable intervention. Refer to the section above.
d) Avoid over-strengthening or over-stiffening. These can change the beneficial characteristics of a masonry arch and lead to future problems.
e) Improve the in-service performance. The intervention should improve resistance to cracking, developing hinges, material degradation and other damages or faults.

f) Avoid significant increases in dead load. A large increase in dead load may overload the foundations or overstress other parts of the bridge.

g) Create a safe working environment. Many strengthening methods may create temporary instability during construction.

h) Minimize disruption to traffic and services. In some cases complete closure to traffic may be impossible, which can limit access to parts of the bridge. The amount of time traffic and services are disrupted should also be a factor.

i) Avoid changing the profile of the bridge. These changes may reduce the amount of headroom under the bridge which may not be acceptable.

j) Accommodate multiple types of defects. Some strengthening techniques may be appropriate for multiple defects simultaneously and should be used rather than using several different methods.

k) Accommodate previous interventions. If the method cannot be installed in conjunction with former interventions, the older interventions should be removed if possible without causing further damage or movements. Alternatively, a different method should be chosen.

l) Avoid local stresses from applied interventions. Compatible mortars, stones and bricks will reduce this affect. When using steel, concrete or other strengthening materials, careful design must be done to prevent localized stresses which can lead to further damages.

m) Offer versatility in design to accommodate additional defects identified during intervention works. Often further defects are revealed as the bridge is worked on and may require additional design if the original intervention will not accommodate them as well.

n) Minimize the impact on the environment.

o) Provide methods with rapid gains in strength. This is important for safety and stability during construction and prevents unpredictable phenomena from occurring during a slow strengthening technique. Also, if the bridge must be closed during construction, it is important to re-open as soon as possible.

p) Accommodate needs for future inspections. The bridge may need to be inspected later to determine if the previous intervention remains in stable condition or determine causes of new deterioration.

q) Be cost-effective within these requirements.

6.5 Repairing and Strengthening Techniques

6.5.1 Grouting

Grouting (or re-grouting) is used to fill voids in the arch ring or spandrel walls. Application to the arch ring ensures that the full depth of section is available in loading. It is often used to fill voids caused by ring separation (or cracks) in multi-ring brick arches or between the ring and backing/fill. For this application, however, it is important to determine if the bond will be sufficient between the grout and existing masonry. If not, cracks are likely to occur at the interface and the intervention is ineffective. In the spandrel walls, grout strengthens against lateral forces by reestablishing the unity of the wall. Grouting in itself does not provide any substantial increase in load capacity, but rather restores the bridge to a former condition and protects the structure from further deterioration. The repair is only minor and is usually done in conjunction with a strengthening technique.

The design of the grout needs to be carefully selected to avoid premature setting before it can completely fill the voids and to ensure its properties are compatible with the existing material. It is important to repair masonry fabrics with adequate and compatible mortars because the properties of a mortar determine the durability, compressive strength, flexural and tensile bond strengths of the masonry. Most historic masonry bridges were built with hydraulic lime mortars. The hydraulic degree in these mortars range from feeble to eminent and is due to their lime binder, added pozzolans or the aggregate used for their fabrication. Through experimentation, it has been shown that lime mortars are more compatible with most masonry materials than artificial cements as lime mortars are porous, permeable and flexible, they do not contain elements capable of forming salts, they develop a good bond with masonry units and their compressive strengths are suitable to withstand typical stresses in masonry structures (Pavía, 2006).

Although hydraulic lime mortars are more common in historic masonry, non-hydraulic (or fat) limes were also used. While hydraulic limes harden due to the chemical reactions between the active clay particles, lime and water (hydraulic set), non-hydraulic limes harden due to a reaction between their CaO and atmospheric CO_2 (known as carbonation). The properties also differ. Hydraulic mortars show more mechanical strength due to hydraulic set, a lower permeability and flexibility, and a better resistance to moisture, frost and salt attack. Fat limes have higher permeability, flexibility and plasticity, significant solubility in water and a low mechanical strength.

Thus, it is evident the importance of carefully selecting the mortar composition in order that the repair matches the physical properties and composition of the existing masonry. To follow conservation principles and provide a compatible interaction, it is advised that lime mortar be preferred over artificial hydraulic cements for the fabrication of masonry repair mortars. In addition, using a sharp, fine, well-graded aggregate, carbonation aids such as porous aggregate and setting aids such as pozzolans will increase lime mortar strength and accelerate hardening, which in turn allows an early strength gain and resistance to adverse weather. Through experimentation (Pavía, 2006), it has been found that fat limes are advised in more ductile, porous and weathered masonry located in sheltered areas, while hydraulic limes are advised in stronger masonry located in aggressive environments.

Grout can be applied using hand tools for easily accessible areas. When applied to the intrados, low pressure grouting may need to be used. Pressure grouting may cause damage to weak structures and should be kept below 1 N/mm^2. The viscosity of a repair grout is important depending on the size of cracks and voids of which to fill. Also, for overhead applications viscosity is of importance to prevent the grout from flowing out of joints. A relatively fast setting time will help in overhead applications.

Grouting can be done relatively quickly and with little or no traffic disruptions. Service disruptions are unlikely although there is risk of seepage into the service area, but this usually does not affect the services. Attention should be taken to not fill any drainage holes of the structure with grout. Removing grout, particularly from inside the structure can be a tedious and a difficult task.
Costs of grouting are low and the main cost come from the number of workers and time spent. Well experienced grouters may cost slightly more, however is recommended to preserve the aesthetic look of the bridge. Grouting may be noticed after completion, however if done neatly, it is usually an improvement to the appearance of the bridge.

6.5.2 Repointing

Repointing is often considered routine maintenance rather than a repairing technique. It is simply the process of refilling deteriorated joints between masonry units. It may restore the load capacity of an arch by restoring the structurally effective arch ring thickness to its full depth, but does not increase load capacity. It may also prevent the bridge from deteriorating further to a point that requires more expensive repair work. However, a poor repointing job can accelerate deterioration of the structure. For example, the mortar must not be too soft or the arch will continue to behave with a reduced thickness; nor should the mortar be harder than the brick or stone which can lead to cracking in masonry units among other incompatibility dysfunctions. As mentioned in grouting repair, it is important to select a mortar with compatible properties to the existing structure.

For proper repointing, raking out of the joints (cleaning and removing top surface) should first be done to a minimum depth of 15mm, however, 25mm is preferable. The depth should be uniform and square. Power tools should be avoided if they may cause more damage to the masonry work. Bucket handle or struck and weathered joints (Figure 6.5) should be used for finishing as they contribute to brickwork durability because the tooling of the joints reduces the permeability of the mortar surface and improves the seal between the bricks and mortar. Recessed joints can increase the level of saturation along the upper arises of the bricks and may lead to frost and damage.

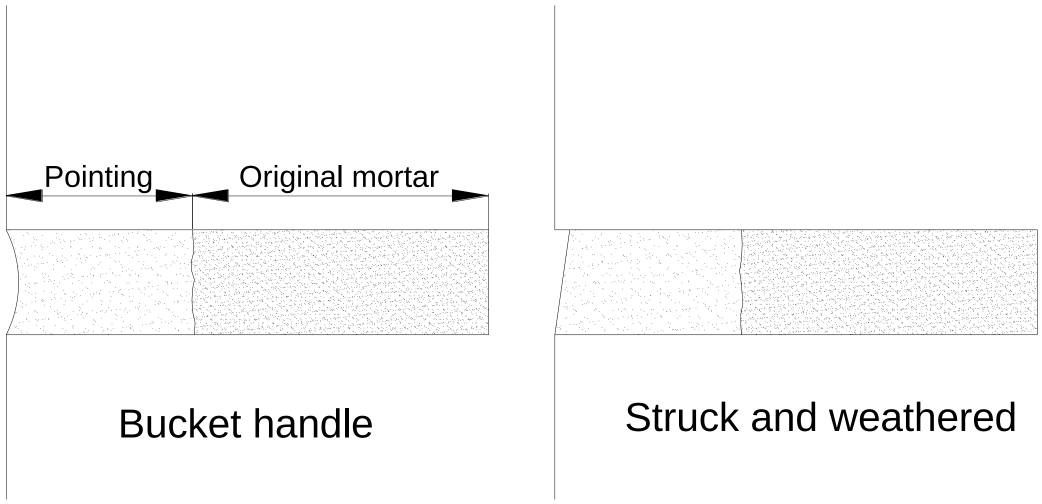


Figure 6.5: Preferable repointing joints

During the process of repointing, it is also an appropriate time to replace any deteriorated or missing units in the same fashion as discussed in the section on replacing units.

Spalling and cracking of mortar has been noticed in some applications of repointing, possibly due to incorrect preparation of the joints, frost, incorrect application of mortar, shrinkage of mortar, water seepage, or growth of vegetation. In this case, the appearance can be negatively affected and the poor application can cause further deterioration of the masonry.

Costs of repair are low and traffic or service disruptions do not occur except possible short delays in waterway traffic. Repointing repair works can prevent the bridge from needing larger, more expensive strengthening techniques in the future. If improperly installed, later removal can be difficult and damaging to the masonry.

6.5.3 Injections

Similar to grouting, injections use grout to fill voids in the fill and backing (above the arch and in the piers or abutments), deeper than near-surface. The injection fill can increase load capacity by improving load distribution to the arch and abutments or piers, and by increasing the weight of the piers or abutments to resist horizontal thrust. It can also be a preventative measure to slow further deterioration of the structure. Injections will reduce the amount of water percolation through the structure. Caution must be taken in the additional weight added by the injected grout and if the structure (particularly the foundations) can take the increase in dead load. The precautions that were discussed in grouting repair apply for injections as well.

For installation, a matrix of holes is drilled into the structure, flushed with water to clear debris, and then injected with grout starting at the lowest point and working upwards. Grout is injected with a pressure grouting machine until the pressure limit is reached, until it appears at adjacent holes, or until a predetermined amount has been injected. Pressure should be kept to a minimum as not to cause internal damage to the bridge. After injection, the hole is plugged with a core from the drilling or other piece of brick or stone with similar appearance to the existing material.

Injections are a very difficult procedure to reverse. Only through excavation and replacement of material can an injection be fully removed. Before application of injections, the stability of the bridge after installation should be analyzed to determine if it is an appropriate intervention for the bridge. An example of injections being inappropriate is when the bridge cannot accommodate the additional weight of the added grout. In bridges with services, additional precautions must be taken to ensure they are not damaged due to injections. The procedure itself should not affect the services except if they need to be rearranged. Disruptions to traffic are usually not necessary for the road surface, but slight disruption in traffic under the bridge may be required. If there are concerns of vibrations affecting the setting of grout, traffic may need to be diverted for a short period on the road service. This can avoided if the injections are done during low traffic periods.

If injection holes are properly plugged, the intervention will have no negative effects on the appearance. The costs of injections are similar to that of grouting but will incur additional costs in the amount of grout needed and additional equipment.

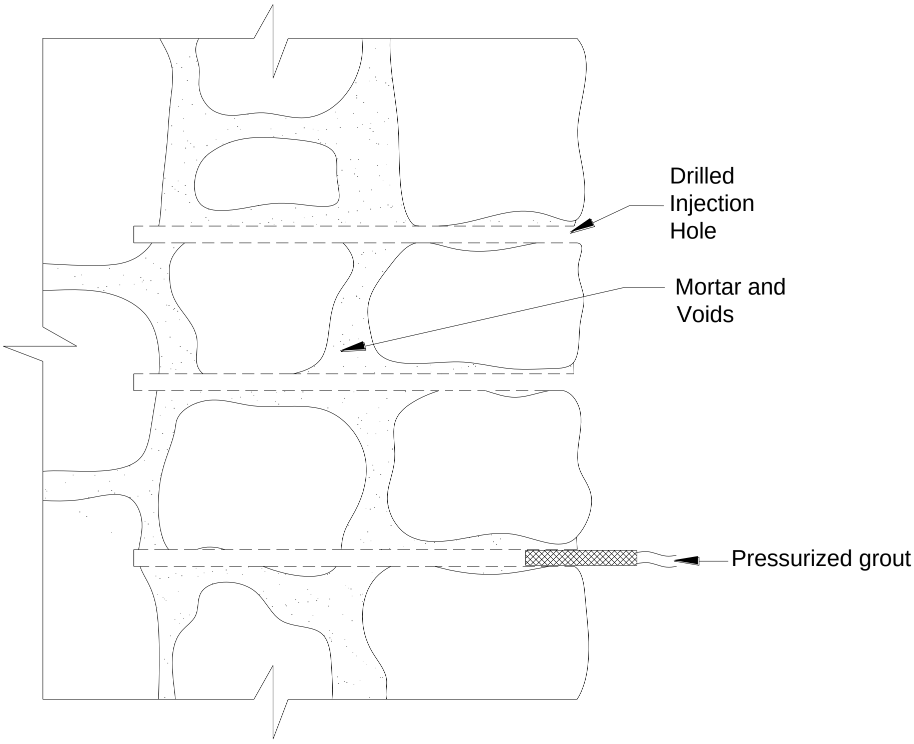


Figure 6.6: Injection scheme.

6.5.4 Replacing Units

Often individual units or a small section in the masonry will deteriorate significantly, particularly those units on the edges which are exposed. It is also possible that local stresses have caused a unit to detach and protrude from the structure. Both cases can reduce the effective section in the arch ring locally and cause more stress in these locations. To regain the effective section in the arch ring and help prevent further deterioration, these units should be replaced. When these units are in the exterior walls, the thinner, weaker section can allow lateral forces to push the wall out, creating a bulge and possibly lead to more severe damages.

Replacing brick or stone should be done with compatible units; not only in terms of material and mechanical properties, but also in color, size and appearance. It is possible to replace a complete ring of bricks if necessary, which can also give a visually satisfying result. In this case, it may be desirable to tie the new ring to the existing structure to ensure proper transfer of loads. When replacing parts of the arch ring, it is necessary to provide temporary formwork in order to prevent any undesirable movements or collapse. During the process, structures with mortar joints will require repointing and grouting in conjunction with it. The same considerations concerning compatibility and procedures should be taken as mentioned in the section on repointing and grouting.

Replacing individual units is a fairly simple and low-cost method of repairing which will also prevent the problem from developing into a more serious damage. Slight traffic disruptions under the bridge may be necessary while the road surface traffic should not be affected. Service disruptions are not caused during repair. Proper selection of replacement material will improve the appearance and respect the original structure.

6.5.5 Saddling

Saddling is a particularly common repair technique found in a broad array of arch bridges exhibiting almost any sign of distress. It involves excavation of the fill and casting of an in-situ concrete arch, which may be reinforced, on top of the existing arch (on the extrados). The concrete is typically of a weaker strength to provide a better compatibility with the masonry. The technique is often combined with spandrel wall repairs, or fill and backing repair and it also allows for waterproofing of the structure.

During the construction of a saddle, the fill is completely excavated to the springings. The excavation is done symmetrically about the crown to minimize risk of movements or collapse in the existing arch or spandrel walls. Spandrel walls may need to be dismantled and rebuilt to prevent damage or collapse. The arch may also need to be supported by centering formwork while excavating and during construction process. After excavation, the arch barrel should be carefully cleaned and any reinforcement placed. Then, any reinforcing or connecting ties should be placed. Drainage should also be installed prior to pouring concrete to allow and escape for percolation of water.

Next, the concrete should be poured symmetrically about the crown of the arch. Saddles may be poured monolithically with varying cross section thickness or may be poured with uniform thickness (Figures 6.7 and 6.8). The use of fibers in the concrete may provide some advantages. Polypropylene fibers give resistance to surface shrinkage cracking, where stainless steel fibers give considerable strength and structural ability to unite arches and to bind cracks. Once the concrete has set, backfill and surfacing may be replaced.

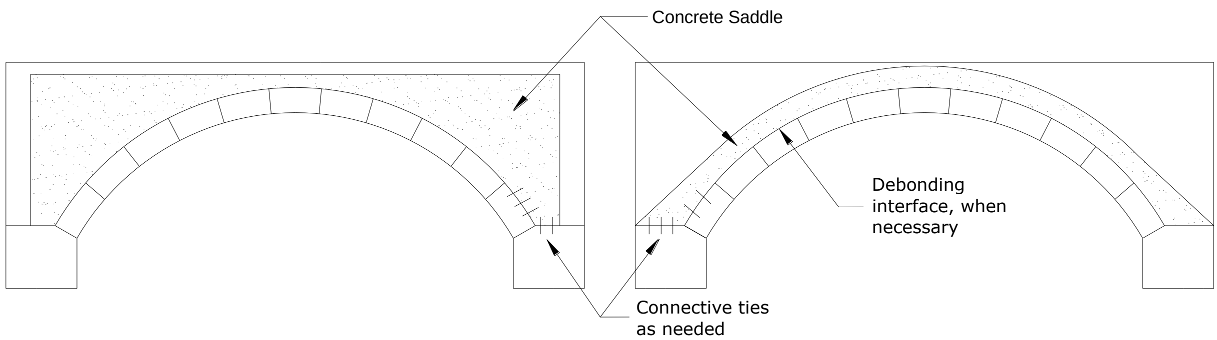


Figure 6.7: Concrete saddles with varying cross section thickness.

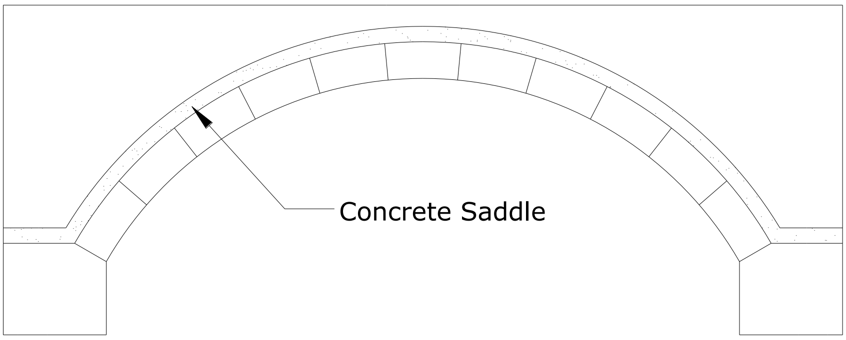


Figure 6.8: Concrete saddle of uniform thickness.

The new arch formed by the concrete saddle is usually designed to act compositely with the existing arch. This will increase the effective thickness and improve distribution of loads. Only nominal reinforcement is likely to be used in this case and a technique of connecting the new arch to the existing arch is needed, such as ties. The ties ensure proper continuity and transfer of forces between the saddle and existing structure. They should be installed into the arch ring, abutment and spandrel walls as needed.

Alternatively, the new arch may be designed to replace the existing arch ring, using it as a type of permanent formwork. In this case it may be debonded from the existing arch, but consideration must be given to the risk of future stability of the arch if it is relieved of loading by the saddle and not tied into it. The lack of stress in the existing arch after saddling could give rise to the possibility of falling masonry blocks. The saddle should be tied to the abutments/foundations when acting as a replacement arch, to allow proper transfer of loading. Additionally, the arch will no longer have the ability to freely adjust to changes in the environment.

As in any strengthening procedure, the reasons for any arch deterioration should be determined and deemed compatible with the strengthening method. A common sign of distress is seen in barrel vaults; this may be caused by movements in the abutments. With the addition of a saddle, the line of thrust will rise, which may increase abutment movement and make the problem worse. Thus, in that case the saddling will not be compatible with the damaged bridge and should be avoided.

The existing abutments sometimes do not have enough capacity for the addition of a saddle. It is therefore necessary to strengthen the abutments in conjunction with the saddling technique (or determine a better strengthening method for the bridge). Spread footings may be built behind the abutments or piled foundations may be used with the saddle and supported by means of spread footings onto a pilecap.

The minimum saddle thickness in which to provide adequate improvement is estimated at 150mm. Therefore, there must be enough cover at the crown of the arch to accommodate this thickness.

Another consideration with the use of saddles is the behavior in the transverse direction. Unlike the longitudinal direction, there are little or no induced compressive stresses and is more likely to be in tension. The transverse restraint at the springing may be enough to cause cracking in the saddle. Thus, it is necessary to consider the sequence of casting for the placement of a saddle.

Saddling provides an intervention that has been successful in almost every case applied and is invisible after completion. However, it requires major construction work which will disrupt the flow of traffic for a long period as well as any services that run through the bridge. Although it is unlikely, if a saddle needs to be removed, it can be difficult and damaging to the structure. Because the length of time and amount of material, saddling can be on the costly side for bridge interventions, especially for larger bridges. However, as it can stabilize several damages at once, it can be economical.

6.5.6 Sprayed Concrete

Sprayed concrete (also referred to as Gunite) is traditionally used to increase the thickness of the arch ring in an effort to increase load capacity and to stabilize and protect weathered masonry. The sprayed concrete is usually applied to the existing intrados of the arch ring. In some rare cases, however, the original intrados ring of masonry is removed and replaced with a sprayed concrete lining to prevent loss of clearance under the arch. This method will require temporary formwork and longer road closure. Other methods of strengthening may be more efficient. The sprayed concrete is often used in conjunction with a reinforcing mesh.

Pre-mixed concrete is sprayed at a high velocity and adheres on impact, filling crevices and compacting material already sprayed. Plasticizers are usually used in the mix in order to gain the right consistency for such application. The concrete is applied in a layer between 150mm and 300mm thick and usually reinforced with a mesh (usually of nominal size steel). The method is relatively quick to apply and does not require long term closure of the bridge (only an adequate time for concrete to gain strength). Nor does it require extensive formwork for application. However, it does reduce the size of the arch opening and does not enhance the appearance or preserve the authenticity of the bridge (Figure 6.9). A better design can reduce the visual impact, such as setting it beneath the arch and slightly set in from the edge of the existing arch, as seen in Figure 6.10. In any case, it is necessary to include additional abutment support for the concrete arch by adding to the existing abutments, attaching a pedestal support to the existing abutment or by cutting into the existing abutments if they are stable (Figure 6.11).

Figure 6.9: Sprayed concrete applied to face of arch ring. (Page, 1996)

Figure 6.10: Sprayed concrete set in from edge of arch ring. (Page, 1996)

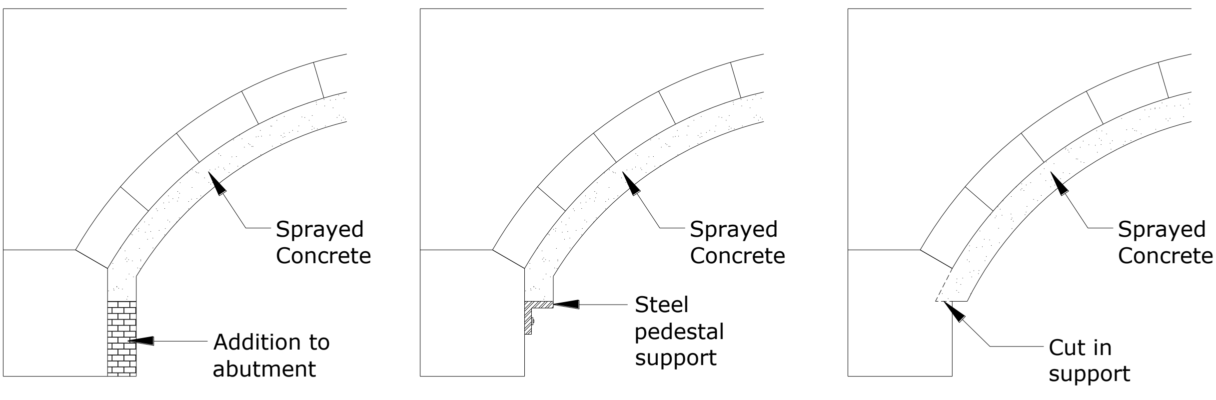


Figure 6.11: Providing additional abutment support for sprayed concrete arches.

With sprayed concrete, it is important to account for the current condition of the masonry. If the arch is already in poor condition, the concrete lining can accelerate deterioration, particularly by trapping water in the arch if the structure previously had inadequate waterproofing. The concrete lining may then become the structural arch, with the existing arch now only a fill. It is possible to design the sprayed concrete in this way from the beginning. In any case, drainage paths are important.

Sprayed concrete can be applied by three different processes; dry, wet, or composite. The dry process uses batched cement and surface-dry aggregates loaded into a mixer. The dry mix is pressurized and evenly introduced, without segregation, into a high pressure and high velocity airstream which carries the mix through a flexible hose to a discharge nozzle. A fine stream of water is introduced at the nozzle to hydrate the cement and provide the desired consistency for placing and compaction. The concrete can be placed at a low water:cement ratio and with no slump. This allows it to be placed on vertical and overhead surfaces; however, admixtures and reinforcement fibers can be added to aid the placement on these surfaces. Aggregates are typically 10mm maximum size and the aggregate:cement ratio is in the range of 3.4-4.0:1. A high amount of coarse aggregate material can rebound during application. Care should be taken to prevent polluting the surrounding environment. A 28 day compressive strength is usually between 30-50 N/mm^2.

The wet process is a pre-mixed concrete which is pumped through flexible hoses to a discharge nozzle. High pressure air is introduced at the nozzle to provide velocity to project the concrete and compact it on the arch. Admixtures such at plasticizers are often used to give the workability needed for pumping. In addition, quick setting admixtures may be added at the discharge nozzle. This method also allows for application on vertical and overhead surfaces. Rebound of the material is typically lower than the dry process and the maximum aggregate size is normally 20mm. A 28-day compressive strength is in the range of 30-50 N/mm^2. This method can cause problems with achieving proper adhesion.

In the composite process, concrete is pre-mixed (concrete, aggregates, and water) and loaded into a placing machine as a wet mix. A high pressure and high velocity air stream is introduced which carries the mix to the discharge nozzle. The better control of concrete quality and water:cement ratio associated with the wet process, and the lower water:cement ratio and higher placing velocity associated with the dry process are possible with this method. In addition, no admixtures are necessary.

Each process can typically show signs of cracking, seen by the seepage of water and the associated leaching of mineral salts. Shrinkage of the concrete or further deterioration of the existing arch may cause separation of the lining from the arch. The load capacity is decreased with separation, and grouting of the interface may be necessary. Any steel reinforcement causes concern for corrosion damage and need for sufficient waterproofing.

Sprayed concrete is a quick and simple technique and will not affect services in the bridge during construction. A small amount of traffic disruptions are needed to allow the concrete to properly gain strength without vibrations. Under bridge traffic will need to be diverted during application. Both disruptions can be minimized by choosing low traffic periods for installation. Costs are less expensive than saddles because excavation is not needed and the number of man hours is significantly decreased. Visually, however, it can be very degrading and is not recommended for any bridges of historical or cultural value. The layer of concrete will also decrease the amount of headroom in the arch.

6.5.7 Pre-Fabricated Liners

Prefabricated liners are typically made of corrugated metal or glass reinforced cement and attached to the intrados of the arch. The space between the liner and arch ring is filled with concrete or grout. The liners provide an increase in load capacity by supporting the arch and giving it more resistance. With the concrete between the liner and arch ring the thickness of the arch is increased which in turn also increases the load capacity. In addition, when filling the space between the existing arch and liner, cracks, missing mortar and voids will also be filled in. Care must be taken to ensure the space is fully filled in to maintain the increased section across the whole arch.

The shape of the existing arch should first be accurately surveyed to provide a good fit and space for concrete. A liner must be manufactured for the shape of the arch. The liner is attached to the arch by supports at the springers or with some kind of bolted anchor system. Concrete is then injected or poured in with the help of chutes. It is important to ensure no voids; the viscosity and setting time of the concrete are important for this reason.

Similar to sprayed concrete, it is quickly and easily applied, and does not disrupt traffic flow above or services. Any traffic under the bridge may be affected for a short period. The span/rise ratio is slightly raised, which also improves capacity. Liners will accommodate movements without severe cracking. Costs are fairly low for this method, both in man hours and material costs.

On the other hand, prefabricated liners reduce the headroom beneath the arch and the width of the waterway. The appearance of the bridge is majorly affected by the procedure and is not preferable for maintaining an authentic appearance. When corrugated metal is used, even when galvanized or coated, corrosion is possible.

Removal is possible but difficult and not recommended. Removing concrete from the intrados will significantly damage the masonry work and possibly pull out individual units (depending on the type of masonry). Prefabricated liners should be reserved for bridges without historical or cultural value and which the appearance is not important and removal is not probable.

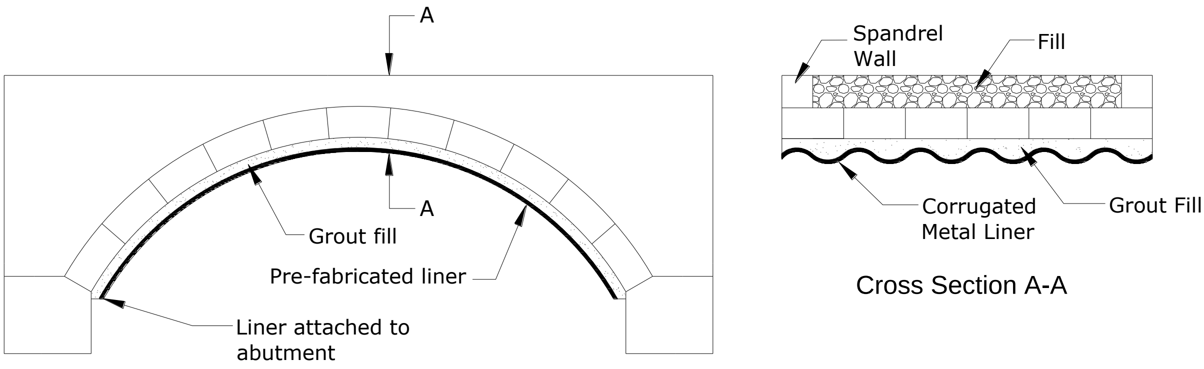


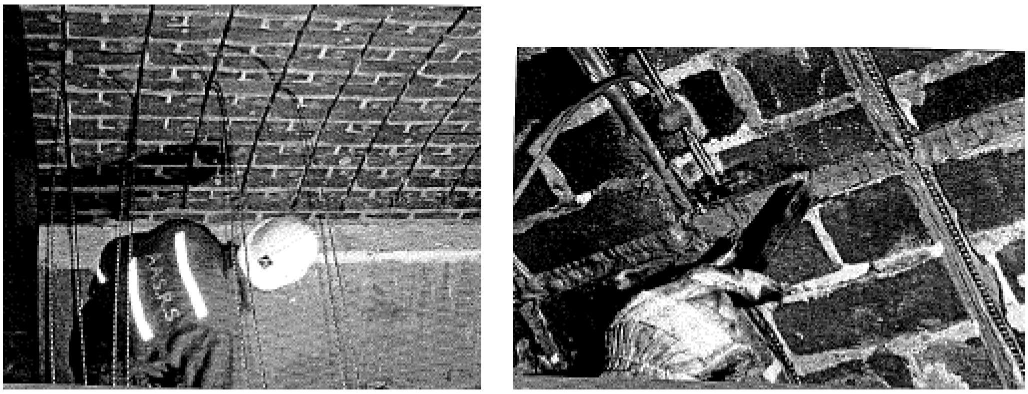
Figure 6.12: Corrugated metal liner.

6.5.8 Near-Surface Reinforcement

Near-surface reinforcement (also called retro-reinforcement) can be used to strengthen a wide range of problems in masonry bridges. It was derived from a technique originally developed for the repair and strengthening of masonry buildings. Stainless steel reinforcing bars are grouted into pre-drilled holes or pre-sawn grooves in the exposed near-surface zones of the masonry where tensile stresses arising from external loads or settlement effects are likely to result in cracking.

The technique uses many smaller sized bars rather than fewer bars with larger sizes. This helps in the case that any of the bars is attacked by corrosion because a small bar will typically not have a large impact on the structure. For near-surface reinforcement to be effective, it must act compositely with the existing masonry. Thus, the selection of grouting material that is compatible with the existing structure is necessary to ensure no increase in local stresses or premature bond failure at the interface of the grout, masonry and reinforcement.

Prior to the installation of the system, grout should be injected where there are large voids or evidence of ring separation. Procedures should be followed as followed as found in the sections on grouting and injections. Once grout has time to set, transverse holes are then drilled into the arch barrel. Stainless steel reinforcing bars are installed into the holes and then grout is pumped into the holes, encapsulating the reinforcement. The reinforcement helps improve lateral load distribution and increases the transverse flexural strength of the arch. To preserve the aesthetic look of the bridge, the holes should be plugged with grout or stone matching the color of the stone. Next, longitudinal grooves are sawed into the intrados of the arch barrel and a grout is injected into each groove. The stainless steel reinforcing is then installed with spacers to provide proper placement and to ensure that each bar is fully encapsulated with grout. Additional grouting is injected over the reinforcing.



(a) (b)

Figure 6.13: (a) Placing bars in pre-drilled holes; (b) Grouting of the grooves. (Summon, 2005)

Another technique which utilizes near surface reinforcement in the arches is a method called Archtec. It is similar to an anchoring technique, and could be included in either section. Retrofitting reinforcement is used to increase the bending capacity of the arch barrel at critical positions and to stabilize transverse cracking (Figure 6.14). The critical positions are often where failures such as hinges will typically develop. Steel is placed at an approximate tangent position to these critical positions in the arch ring. The reinforcement is usually installed from above using accurately positioned drilled holes through the fill and into the arch ring (Figure 6.15). The steel bars are grouted in place using a fabric sock grout delivery system to ensure consistent bond with the surrounding masonry. Placing the reinforcement across transverse cracks can also help stabilize crack growth.

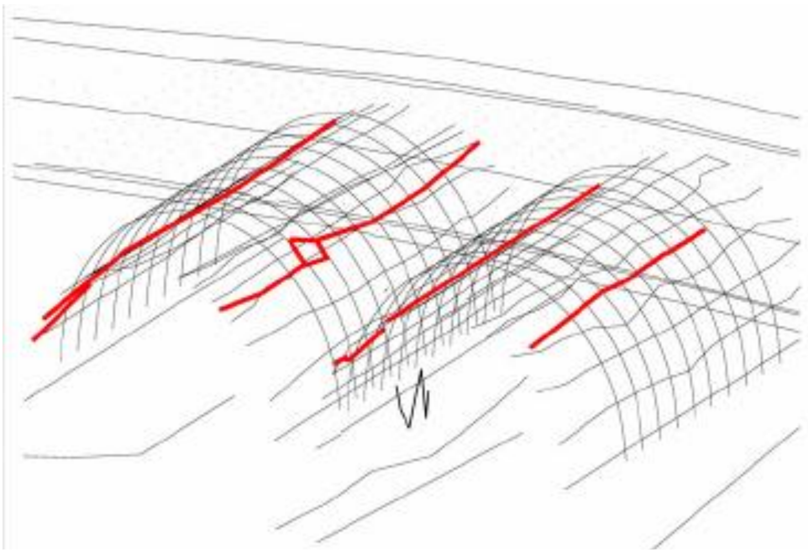


Figure 6.14: Transverse cracking (Brookes, 2004).

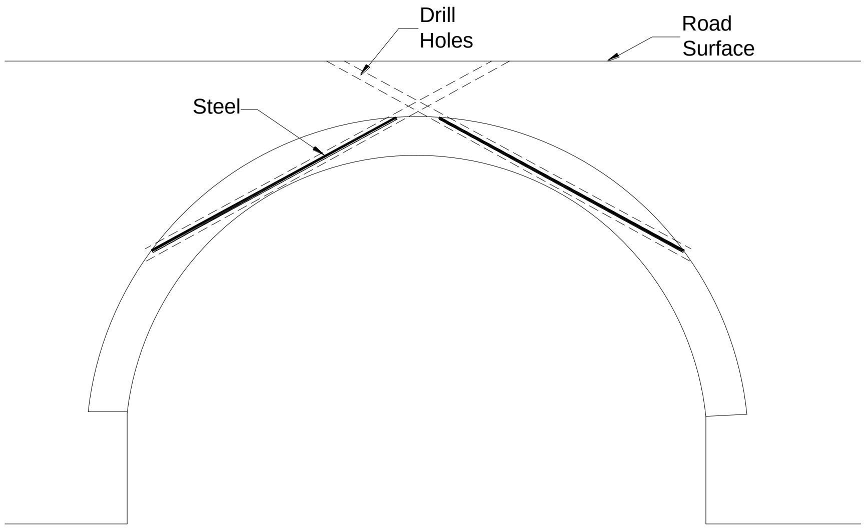


Figure 6.15: Archtec strengthening scheme.

From test results, Archtec anchors are stressed under working loads and are thus contributing to the bridge's stiffness (Brookes, 2004). The method reduces tensile intrados strains, reducing the likelihood of loosening masonry under live loads. In addition, the anchors positioned across transverse cracks reduce the opening and closing of cracks, reducing damage from load cycle derived deteriorations, and thus improving the service life.

The cost of these methods is typically less expensive and less disruptive than others that may accomplish the same results such as saddling, sprayed concrete or pre-fabricated liners. In addition, the construction is easier when compared with these other methods.

In both methods, the bridge usually would not need to be completely closed to traffic, depending on the width of the bridge. Under bridge traffic may experience slight disruptions. If services run through the bridge, the Archtec method may cause disruptions in services. Near-surface reinforcement should not affect services since the work is within the ring of the arch.

Plugging or capping boreholes after reinforcement is installed with grout or with material similar to that of the bridge will allow for practically no effects in the aesthetics of the bridge.

6.5.9 Fiber-Reinforced Polymer (FRP)

Introduction

A polymer (from the Greek *poly* meaning "many" and *meros* meaning "parts") is simply a large molecule of linked structural units, usually by covalent chemical bonds. The physical arrangement of the monomers and the types of monomers present determines its properties. Some forms of polymers include homopolymers, copolymers, and branch polymers. Polymers can be natural or synthetic with a large variety of properties.

Rayon was the first synthetic fiber. Considered as the first precursor to Rayon, Comte de Chardonnet worked on a process of producing threads of an "artificial silk" made from collodion in 1884. Chardonnet's silk was finally marketed in 1891, but was short-lived after a young lady's ball gown went up in a puff of smoke after being touched by the lighted cigar of her escort. Charles F. Cross and Edward J. Bevan patented their formula for viscose, a cellulose polymer, in 1892 and were soon manufacturing items of their new Viscoid. The first viscose thread was made by Charles Topham Jr. and commercially produced in 1899. Rayon, made from regenerated cellulose in 1926, marketed by Du Pont, was finally used as a replacement for silk.

Although many polymers were made in the following years, the technology to mass produce them was not developed until World War II, when there was a need to develop synthetic rubber for tires and other wartime applications such as nylon for parachutes. Since that time, the polymer industry has grown and diversified into one of the fastest growing industries in the world. Today, polymers are commonly used in thousands of products such as plastics, elastomers, coatings, and adhesives. Polymers make up about 80% of the organic chemical industry.

Composite materials are engineered materials made of two or more constituent materials with notably different physical and/or chemical properties, which maintain their separate and distinct properties on a macroscopic level within the completed structure of the material. Constituent materials consist of two categories: matrix and reinforcement. At least one of each category must be present to create a composite. The role of the matrix material is to surround and support the reinforcement material allowing it to maintain a relative position. The reinforcement material allows for the composites special mechanical and physical properties, enhancing the matrix properties.

Combining these two methods, engineers have developed continuous fiber-reinforced polymers (FRP). These types of composites are heterogeneous and anisotropic, commonly behaving linearly elastic up to failure. Some advantages these materials present include their lightweight, good mechanical properties, and corrosion-resistance.

Figure 6.16: Types of FRP material (Pellegrino, 2009).

There are several types of materials used for the fibers in FRP, including glass, aramid and carbon. Glass fibers typically have a Young's modulus of elasticity around 70 GPa, and have a relatively poor abrasion resistance. They are also prone to creep and have low fatigue strength. Aramid fibers consist of organic fibers characterized by their high toughness. Although they have a higher Young's modulus of elasticity than glass fibers, aramid fibers may degrade after extensive exposure to sunlight losing up to 50% of their tensile strength. As they are organic, they can also be sensitive to moisture. Their creep response can be similar to that found in the glass fibers; however, their failure strength and fatigue behavior is higher than the glass fibers.

The last type of fiber used in FRP is the more commonly used in structural engineering applications. Carbon fibers are more typically used because their high performance, high Young's modulus of elasticity and high strength compared to that of glass and aramid fibers. They are also less sensitive to creep rupture and fatigue, sunlight and moisture degradation. The brittle failure behavior with relatively low energy absorption is the main disadvantage of carbon fibers, however the aforementioned properties outweigh these, especially when compared with glass or aramid fibers.

	Young's modulus E	Tensile strength σ_T	Strain at failure ε_T	Coefficient of thermal expansion α	Density ρ
	[GPa]	[MPa]	[%]	$[10^{-6}\ °C^{-1}]$	$[g/cm^3]$
E-glass	70 – 80	2000 – 3500	3.5 – 4.5	5 – 5.4	2.5 – 2.6
S-glass	85 – 90	3500 – 4800	4.5 – 5.5	1.6 – 2.9	2.46 – 2.49
Carbon (high modulus)	390 – 760	2400 – 3400	0.5 – 0.8	-1.45	1.85 – 1.9
Carbon (high strength)	240 – 280	4100 – 5100	1.6 – 1.73	-0.6 – -0.9	1.75
Aramid	62 – 180	3600 – 3800	1.9 – 5.5	-2	1.44 – 1.47
Polymeric matrix	2.7 – 3.6	40 – 82	1.4 – 5.2	30 – 54	1.10 – 1.25
Steel	206	250 – 400 (yield) 350 – 600 (failure)	20 – 30	10.4	7.8

Table 6.1: Comparison between properties of fibers, resin, and steel (Pellegrino, 2009).

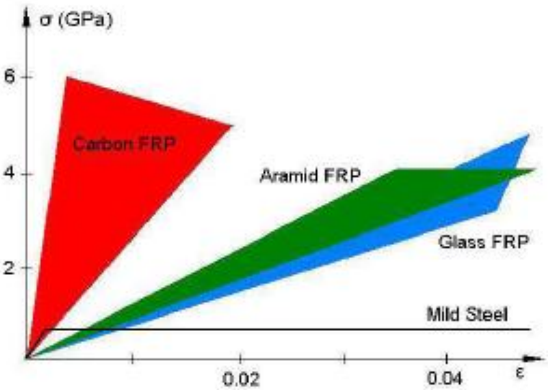


Figure 6.17: Stress v. Strain ranges for polymer fibers (Islam, 2008).

To create a composite a matrix must be added to the fibers. In civil engineering, the epoxy resin is the most commonly used material for matrices. Epoxy resins have a good resistance to moisture, chemical agents, and have excellent adhesive properties. As seen in Table 6.1 the matrix material has a much smaller Young's modulus and strength than the reinforcement material. However, when the two constituent materials are combined together they form a material with different properties. The fibers in the composite provide both loading capacity and stiffness while the matrix distributes the load among fibers and protect them from environmental dangers. The figure below shows a stress-strain relationship between the fiber, matrix, and resulting FRP material. The FRP composite will have a lower stiffness than the individual fibers, but will fail at the same strain, $\varepsilon_{f,max}$, as the fiber material. Beyond that point load sharing from the fibers to the matrix is prevented.

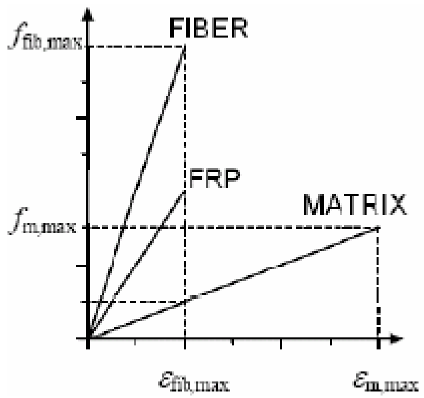


Figure 6.18: Stress v. Strain relationship in a composite (Pellegrino, 2009).

FRP systems which are applied to the external of a structure are usually classified as either pre-cured systems, wet lay-up systems, or prepreg systems. Pre-cured systems are manufactured in various shapes by pultrusion or lamination and are directly bonded to the structural member to be strengthened. They are characterized by a unidirectional disposition of fibers. Wet lay-up systems are manufactured with fibers lying in one or more directions as FRP sheets or fabrics and impregnated with resin to the structure at the job site. Prepreg systems are manufactured with unidirectional or multidirectional fiber sheets or fabrics, pre-impregnated at the manufacturing plant with partially polymerized resin. The systems are delivered in rolls of thin sheets (typically around 0.15 mm) which are flexible and moderately sticky, with detaching film applied to the surface to preserve the bonding system. They can be bonded to the structural element with or without the use of additional resins.

FRP for Strengthening Masonry Arch Bridges

Many traditional methods of retrofitting masonry arch bridges are often labor-intensive and short-lived, and usually violate aesthetic, conservation or restoration requirements. In addition, they often add considerable mass and reduce the available space. Furthermore, FRP does not alter structural behavior and are removable. Only recently have researchers suggested the use of FRP in the form of surface reinforcement for masonry structures (around 1994 the first papers were presented). It certainly seems to be an appealing option in retrofitting masonry arch bridges. The technique has been used in the reinforced concrete field for more than ten years before researchers began experimenting with it in the masonry field.

The typical way to use FRP in strengthening masonry arches has been to apply sheets at the intrados and/or extrados. The sheets are continuous across the surface of the arch to enhance the capacity; non-continuous sheets would not provide significant advantages. The FRP reinforcement will not prevent masonry from cracking, but rather transfers the tension force across the crack, preventing the cracks from opening and creating plastic hinges. The boundary opposite the FRP strip will be prevented from hinging.

As mentioned above, FRP can be applied by one of three different systems (pre-cured, wet lay-up, or prepreg). Each system can provide slightly different mechanical and geometric properties, however, wet lay-up and prepreg systems have been shown very similar. Properties should be obtained from the individual manufacturer for consideration in design. Application of each system is quite easy and only requires a simple bonding to the surface at the pre-defined locations.

The application of FRP sheets to an arch modifies the classical mechanisms of collapse in masonry arches (without reinforcement). The mechanisms are also altered according to which surface the FRP is applied (extrados, intrados, or both). This occurs because the fibers can bear the stresses at the tensed edges of the typical failure sections, which are in combined compressive and bending stresses. The resistance in the arch is now similar to reinforced concrete, dependent on the masonry compression strength and on the fiber tensile strength, which is very high.

Through experimentation at the University of Padova (Valluzzi, 2001), the behavior of masonry vaults strengthened with FRP reinforcement has been assessed. When FRP is applied to the external surface (extrados) of the arch (Figure 6.19a) the line of thrust can fall outside the lower edge of the vault without causing structural collapse. With a vertical load applied at one-fourth the span, the hinge that would normally form at position B is prevented. Thus, the arch becomes an isostatic structure with three hinges. The arch can now be assumed as two curved beams strengthened on their upper sides (Figure 6.19b). This scheme allows the stress parameters in every section of the structure to be obtained through simple geometrical and equilibrium relationships. The stress parameters along the abscissa of the vault are shown below in Figure 6.20.

Strengthening the arch at the intrados creates a similar static scheme, but a different distribution of stress parameters. The line of thrust shown in Figure 6.19c falls outside the upper edge of the arch and the fiber reinforcement prevent the hinge formation at the position of the load. Consequently, the external load is no longer a nodal position of the static scheme. Thus, the trend of the stress parameters changes as shown in Figure 6.20.

To assure the maximum load-bearing capacity of the arch, the reinforcement must prevent a fourth hinge from occurring, only allowing the following failures: (1) crushing, (2) sliding, (3) debonding, or (4) FRP rupture. These failure modes are dependent on the limits of strength of the constituent materials and on the structural interactions of them at a local level (Valuzzi, 2001). For instance, inevitable irregularity of the masonry surface can lead to a poor bond between fibers and the masonry and to a consequent negligible strengthening effect. When the arch failure is dictated by the mechanism, an ultimate load analysis such as the lower and upper bound theorem can be used. However, when failure is dictated by one of the previously mentioned failure modes, specific methods must be used for analysis. For more information on analysis methods and failure modes in arches strengthened with FRP, refer to Appendix A.

Analysis has shown that a small quantity of surface FRP reinforcement can significantly increase the load-bearing capacity. The amount of reinforcement depends on the arrangement of the reinforcement; spacing and width of strips, and the number of blocks a strip is bonded to. With the proper arrangement of FRP to prevent the collapse mechanism, the bridge will experience a significant increase in load-bearing capacity, a reduction in lateral thrust, and a more certain and predictable ultimate behavior. For further documentation on design and construction, the following source should be consulted: CNR-DT 200-2004 “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures”, 2004.

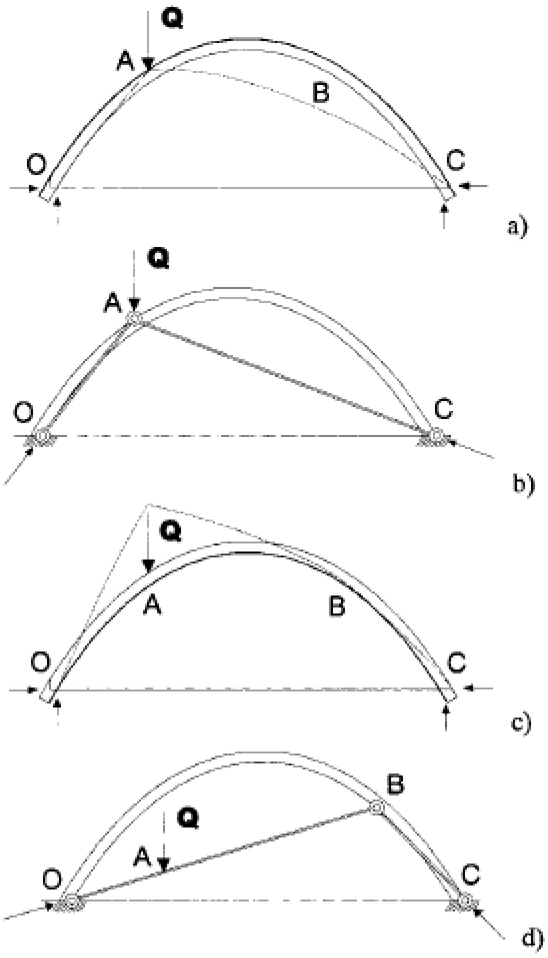


Figure 6.19: Line of thrust and static scheme of a vault strengthened at: (a,b) extrados; (c,d) intrados (valluzzi, 2001)

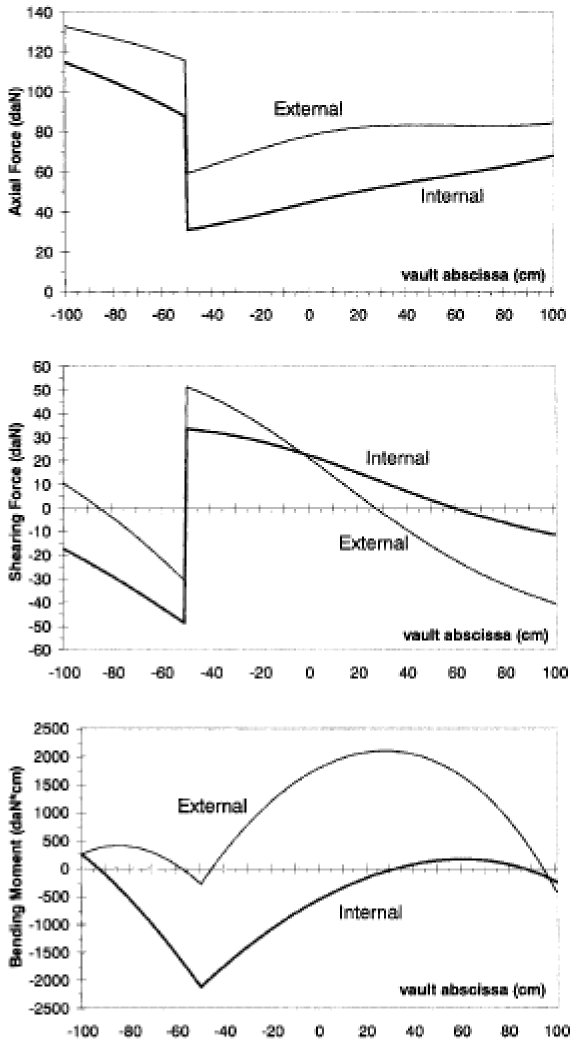


Figure 6.20: Comparison between trend of stress parameters of strengthened vault for internal and external reinforcement (valluzzi, 2001).

FRP strengthening is certainly not as labor intensive and has a longer life than other strengthening techniques. Particularly when FRP is only applied to the intrados, installation can be completed very quickly and usually without traffic or service disruptions. When application is required on the extrados, traffic and service disruptions should be planned on.

Conservation guidelines are well followed using FRP; the only aesthetic alteration will be to the intrados when applied in this location, but is little noticed. Long term affects on the appearance such as corrosion discoloration, is also not an issue as the material has an immunity to corrosion. Furthermore, the method can be fairly easily removed from the intrados if it is found to be negatively affecting the structure or another method is found to be better for the structure. Removal from the extrados can be more difficult, as it requires excavation of the fill and backing.

Although carbon reinforced fibers are expensive, the full method of applying FRP is usually significantly cheaper than that of other strengthening methods. The savings come from the ease of construction with little equipment needed, a small labor force, and very little time for application.

6.5.10 Anchoring

Anchoring (also called stitching or tie bars) can be an economical alternative to methods requiring extensive dismantling like saddling. When significant longitudinal cracking (see Figure 4.5) becomes present in the intrados of an arch or spandrel walls are detached, tilted or bulging from its backing, anchoring is a viable option for restoring shear transfer and continuity. Ring separation occurs more often and a type of anchored called radial pinning can be used to restore the loss in integrity caused by ring separation and prevent further separation. Both processes may require replacing or resetting some units in the intrados or spandrel wall, as well as repointing and/or grouting. The same procedures found in the corresponding section should be used.

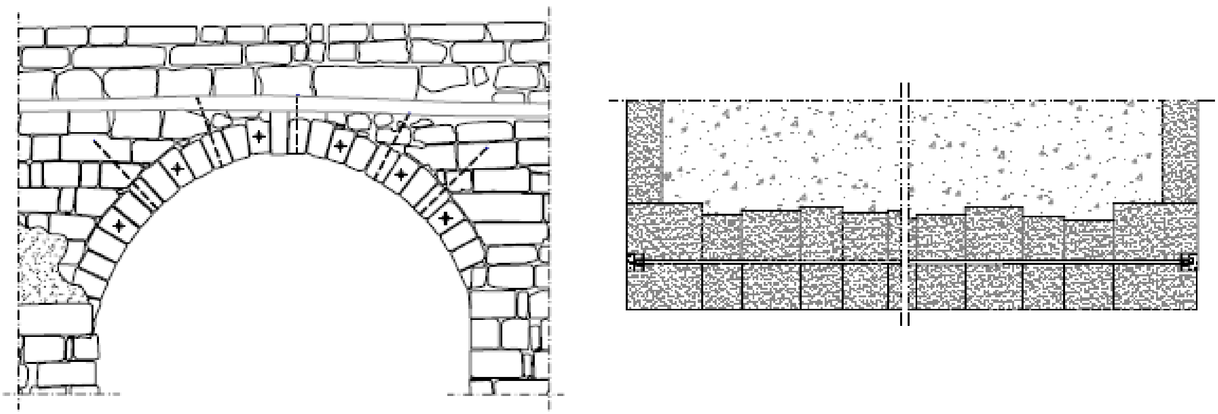
After replacing and resetting, oversized holes are drilled using a rotating drilling device through the full width of the bridge or through the ring to a pre-defined depth into backing and fill. The anchors can be designed using retaining wall theory. There is no specification known at this time relating to suitable spacing for tie bars. Engineering judgment should be used in deterring spacing.

After holes are drilled, stainless steel rods incased by a sleeve are placed in the holes and then grouted under low pressure. As with any intervention involving the addition of grout in historical masonry, care should be taken in the selection and compatibility (refer to the section on grouting for more detail). The sleeve prevents grout from being lost in voids. The rods are secured to steel anchorage plates at each side of the arch (only on the visible end for radial pinning). To help prevent corroding, grease or other sealant should be used over the exposed bar and plate. Corrosion can cause small, local movements in the structure and corrosion stains. To decrease negative visual effects from the intervention, the plates are usually set in from the face of the stone and plugged with grout and a cylinder of stone from the borehole (Figure 6.21). In some cases the radial pinning may be done on the outer face of the arch and walls, however, this greatly affects the visual appearance of the bridge.

a) b) c)

Figure 6.21: (a) Cylindrical shaped anchor plate used in anchoring; (b) stone cap taken from drilled core; (c) final appearance of neatly plugged anchoring. (Oliveira, 2006).

If the spandrel walls require anchors near the road surface, it is possible to drill or saw a trench in the road surface to insert the bars rather than drilling through the bridge. The trenches are grouted and road surface repaired. While this is easier than drilling through the bridge, it does require traffic closure during the process.



(a) (b)

Figure 6.22: Strengthening system using anchors and radial pinning; (a) anchor scheme; (b) cross section showing horizontal anchor (Oliveira, 2006).

Anchoring and radial pinning will increase the stiffness and the elastic properties of the arch barrel and limit movement. The radial pins restore the full thickness of the ring in the case of a multiple layer ring, and otherwise restores the integrity. If both the arch and spandrel walls need strengthening, an alternative solution is to use a concrete saddle which will relieve the spandrel walls of outward forces and increase the capacity of the arch. The decision may be one of economics and depends on the amount of anchors or thickness of the saddle, length of construction, and necessary equipment as to which will be the most economical. A saddle will provide the most hidden intervention though and should be considered in this case, particularly for bridges where appearance is important.

Slight road surface traffic disruption may be necessary while stones are reset and replaced. Vibrations from live loads are not preferable during this stage. If the bars are installed from the road surface via trenches, road closure is certain, but can be kept to a short period. Traffic below the bridge will usually experience short delays during installation. Horizontal anchoring through the arch ring should not affect services, however with radial pinning and spandrel wall anchoring services should be located and appropriate steps taken to prevent damage.

Drilling horizontally through the fill can be difficult. Otherwise, construction is relatively simple and typically less expensive than excavating the fill and backing to do repairs. Once construction is complete there is little change to the appearance as long as the anchor plates are capped or plugged. However, if the rods, plates or fastenings corrode, staining of the surface may occur.

6.5.11 Relieving Slabs

Relieving slabs (also called overslabbing) are flat reinforced concrete slabs placed on top of the fill. It improves the bridge through better distribution of loads on the arch and alters the line of thrust to allow appropriate load transfer to the abutments. In some cases a compressible layer is installed under the central section of the slab to relieve the arch of more live load. Lateral pressure on the spandrel walls is reduced and the slab allows for a good waterproofing to keep water out of the structure.

Relieving slabs are similar to saddles except they are not placed directly on the extrados of the arch. The amount of excavation depends on the condition of the current road surface and the desired load transfer. If an increase in the road height presents no problems and rearranging of the fill is not necessary, it is possible for the slab to be applied directly on top of the current surface with little or no excavation. It is recommended at minimum to remove the current road surface and place the slab over the fill. On the other hand, if the same height is desired or improvements are needed in the fill and/or backing for possibly load distribution purposes, fill will need to be excavated to a pre-defined depth. Excavation should be done symmetrically on both sides of the crown.

After the required excavation has been completed, if repairs to spandrel walls are necessary, it is a good opportunity to take care of these. Whether they need to be rebuilt or an anchoring system needs to be added, it is easier to do with an excavated fill.

Design of the slab will be the same as a concrete roadway supported at two ends. Reinforcement, clear cover and other design considerations should comply with the local codes for road surfaces. Traffic must be closed to at least half of the bridge and services should be located to determine if the depth of excavation will affect them. Under bridge traffic will not be disrupted. Relieving slabs will be cheaper and easier to construct than saddles.

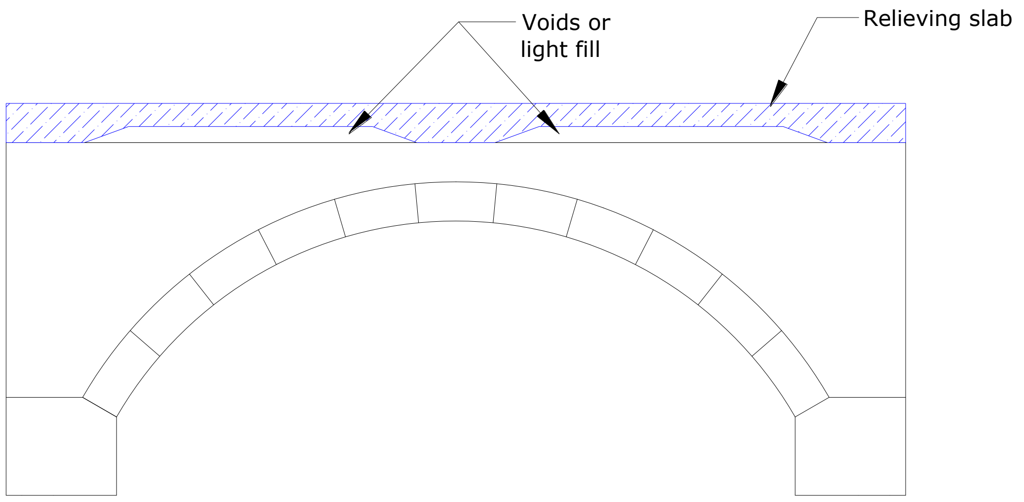


Figure 6.23: Relieving Slab

6.5.12 Replacing with Concrete

In some cases, rather than dealing with injections to fill all the voids in the fill or backfill, the entire space will be replaced with concrete. This provides a known continuity throughout the fill which provides a better distribution of loads. The additional weight can alter the line of thrust to a more preferable location. In addition, this will help stabilize sliding, bulging or tilting of spandrel walls. The method is very similar to saddling and when repairs are also required on the arch both interventions can be done simultaneously.

The material behind the spandrel wall is excavated down to the springer or pre-defined depth of the pier or abutment, symmetrically on both sides of the arch. If not done in conjunction with saddling, it is not necessary to excavate the material above the arch. A low strength in-situ concrete is then used to fill the areas symmetrically in layers. Pouring symmetrically prevents irregular loading on the structure while pouring in layers prevents the wet weight of concrete from applying too much lateral force on the spandrel walls. Cold joints should not be an issue, but consideration may be taken in tying layers together. Typically, reinforcement is not necessary, however in cases of weak spandrel walls or to improve the bond between the two, steel bars may be implemented as a type of anchor to secure the spandrels. Concrete should be poured symmetrically when filling both sides of the bridge and in layers as not to cause movements in the spandrel wall from the wet weight of concrete. Formwork may be required during the excavation and pouring of concrete to ensure no movements in the structure.

The intervention is invisible after completion and allows the opportunity for strengthening parapets, addition of anchors, installation of a full saddle and installation of subsoil drainage, simultaneously. The main disadvantage is that traffic and services will be heavily disrupted during installation. Removal of the concrete, if needed, may be simple in procedure, but can be tedious and take time. In addition, vibrations from equipment used to break up the concrete for removal may cause damages to other parts of the structure.

Cost efficiency of this method can be questionable, particularly when the entire fill is to be replaced. The mass amount of concrete and amount of time to excavate the fill add costs quickly. Usually the bridge will have more damages and faults than what this intervention can correct alone. Thus, consideration should be taken on whether this is the most appropriate method for the given bridge.

6.5.13 Invert Slabs

An invert slab is a slab of concrete (older interventions may be built with masonry) placed between the abutment walls or piers with its top surface at or below river bed level. The method is used in bridges which cross over flowing water and it helps prevent scour of river bed under the foundations. Often times a downstand beam (deep beam) at each end of the slab will be installed to increase the protection against scour or undercutting of the slab itself.

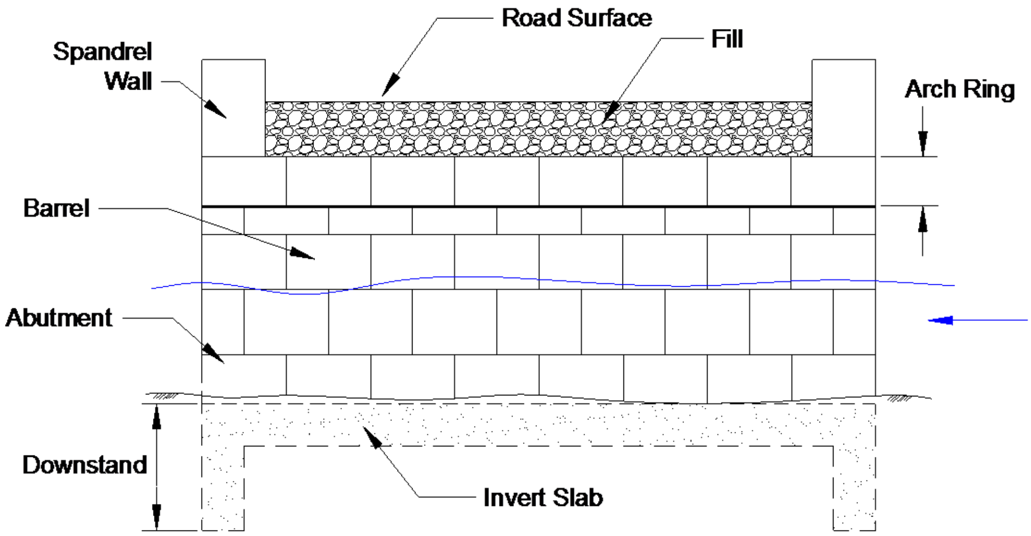


Figure 6.24: Cross-section through invert slab with downstand.

Invert slabs may also be used to prop the abutments apart if inward movement has occurred or seems prone to occur. However, this may not be useful in particular cases if the inward movement is at the springers and not at the base of the pier. In Figure 6.25a, there is rotating and inward movement at the base of the pier due to a horizontal thrust of which the pier or soil conditions are not adequate to resist. The slab then resists inward movement that could result, shown by the dotted line. On the other hand, if inward movement is occurring at the springers due to a horizontal thrust, the base of the pier may move out away from the slab (Figure 6.25b). This is typical in multi-span bridges where one arch is applying a greater horizontal thrust than its adjacent arch. In this case, the foundation can crack or separate from the slab, introducing voids that can allow scour to occur between the pier and invert slab. A solution in this case may be to consider underpinning and strengthening elsewhere to prevent the movement. This is not the only behaviors abutments and piers may have as a result of these or other forces or damages. Appropriate assessment of the effects the slab will have on the structure should be done prior to installation to prevent such incompatible installations.

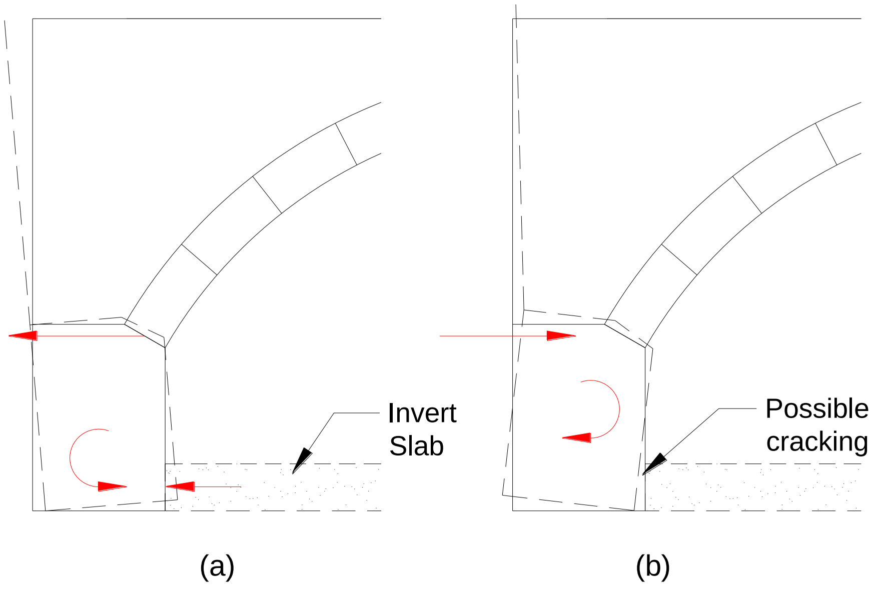


Figure 6.25: Propping abutments with an invert slab.

The slabs should typically be reinforced using nominal steel with appropriate clear cover for underwater concrete. The design is typically done as a slab supported at each end. Additionally, proper strength requirements to prop the abutments should be considered in the design.

Invert slabs are particularly suitable in multi-span bridges where the middle piers will have running water and thus a higher risk of scour from both sides. Having multiple spans also helps in the ease of construction, where the flow through one or more arches may be dammed during installation. Damming or diverting water is preferable for installation, allowing placement and set of the concrete in a dry environment (rather than underwater). Where bridges cross large and/or rapid flowing water, this is often not possible. In this case, divers may be required and proprietary underwater concretes which are fast setting should be used. Precaution should be taken in the type of concrete used in either case to prevent water pollution due to the escape of cement or toxic additives. More information on underwater concretes can be found in the references by Staynes and McLeish.

Construction should be scheduled around times of minimal water flow to allow for damming or diverting of water and assist in the ease of construction. Constructions which are not scheduled appropriately or are in locations with constant large and/or rapid flows will cause a significant increase cost.

If invert slabs are incorrectly installed (for example, the slab is high relative to stream flow), there is a higher risk of scour beneath the slab, particularly at its downstream end. Overhangs and progressive collapse of the slab are a possible result. It may also increase turbulence and aggravate the effect.

The installation of downstands or sheet piling (Figure 6.26) can be helpful in preventing this because it provides an additional depth of the slab at the downstream and upstream ends which is less prone to scouring.

Sheet piling consists of a series of panels with interlocking connections, which are driven into the ground with impact or vibratory hammers to create an impermeable barrier. A variety of materials may be used to make sheets including: steel, vinyl, plastic, wood, recast concrete and, fiberglass.

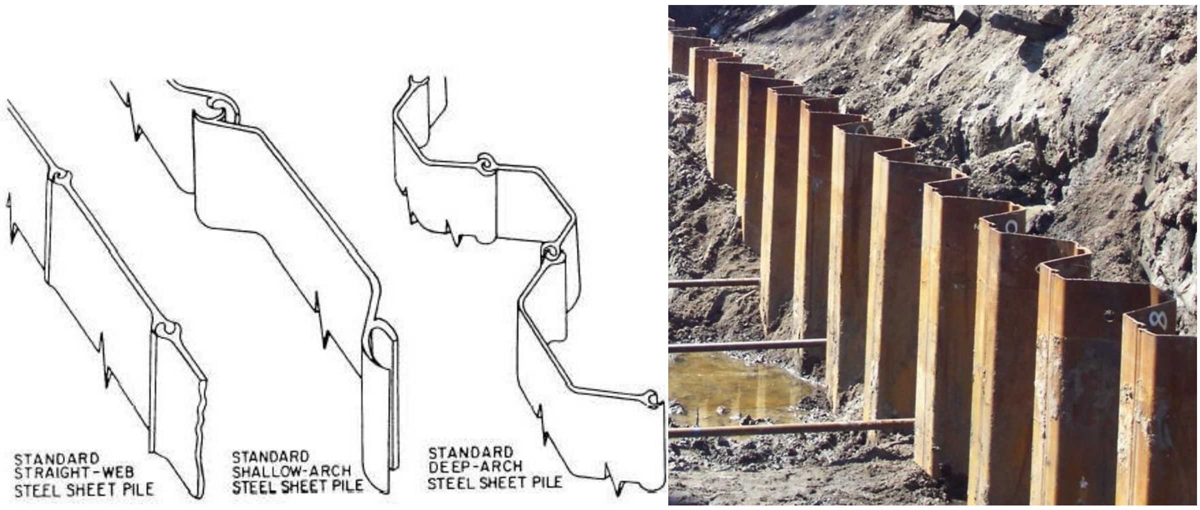


Figure 6.26: Types of sheet piling and an example of sheet piling. (www.tpub.com)

Whether installed correctly or not, the addition of an invert slab can cause scouring in other areas and should be considered. Downstream erosion is also a common problem resulting from installation of an invert slab. Consideration should be given to the provision of river bed protection to some distance from the structure. As conservation should be approached with a multi-discipline team, the use of a water resources engineer is recommend in the design and installation of invert slabs.

Typically, invert slabs are a low cost and speedy intervention, assuming none of the difficulties mentioned above. The construction process does not disrupt road surface traffic and typically does not disrupt services except in the case of those on the stream bed near the bridge. Waterway traffic will be disrupted during installation. The method has been shown to arrest or delay scour by sealing the river bed and by reducing turbulence. Invert slabs also provide a firm river bed which may be useful in the future when further interventions may be done on the intrados of the arch (i.e. provides a firm foundation for scaffolding or other supports). In addition, they can be removed (with the proper precautions) fairly easily if found to be negatively affecting the bridge.

Regarding visual effects and authenticity, invert slabs are very efficient. The intervention will not be seen after completion and the appearance of the bridge will remain the same.

6.5.14 Underpinning

Underpinning is similar to invert slabs and involves excavating of soil and other material from beneath the existing foundations and replacing with mass concrete. Underpinning is useful in stabilizing the foundation, preventing future damage from scour or settlement. It is also useful for bridges where stream beds have been lowered, whether by natural causes or by dredging to provide deeper water for ships. Reinforcement is not always necessary in the mass concrete itself, however, it may be important to tie the concrete into the existing foundation and if used in conjunction with an invert slab, it is necessary to tie into the slab as well.

Underpinning is a labor intensive technique which usually will not provide full penetration beneath the abutment or pier, as seen in the figure. It requires diverting of water flow or a cofferdam and the working area must be cleared of water. Thus, as less flow means less hydraulic force, the process should be done when the water flow is at a minimum to provide ease in altering the water flow. This will help provide an easier construction and save additional cost from rapid and high water flow. The foundation or structure may need a temporary supporting system while the soil is excavated and while the concrete cures. It is recommended that the bridge be in otherwise stable condition before commencing construction.

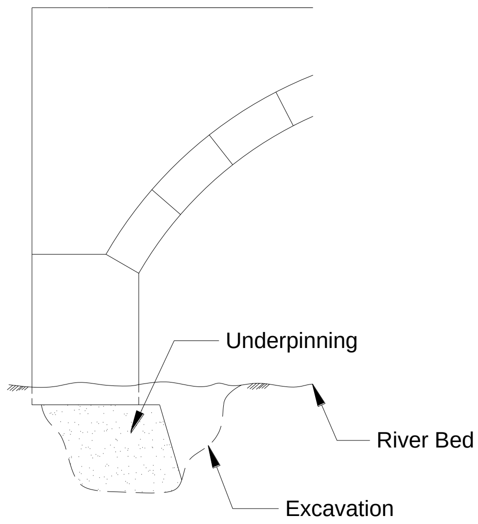


Figure 6.27: Underpinning.

As with invert slabs, working with a water resources engineer is recommended when implementing underpinning. In addition, a geotechnical engineer may be helpful to ensure proper consideration of the soil beneath the piers and abutments. Soft ground, running sand, expanding clays or other soils may cause difficulties in construction or lead to movements in the pier or abutments during excavation.

If underpinning is found to be negatively affecting the structure after installation and removal is necessary, difficulties will exist. The foundations can be damaged even further during removal and is not recommended. Therefore, it is important to carefully assess the affects the installation may have on the structure prior to construction.

Although the process is labor intensive, the design and construction are simple. The required materials are low cost and low strength (typical 20 N/mm^2 strength concrete is normal). Equipment for providing cofferdams or diverting water incurs a large percentage of the costs. Disruptions to road surface traffic or services are not likely. Waterway traffic may experience slight disruption, depending on the span length or number of spans. Previous applications of underpinning have been successful.

In addition, the intervention will not be seen after completion and the appearance of the bridge will remain the same, thus respecting the guidelines of conservation.

6.5.15 Stone Pitching

Stone pitching is a more primitive way of gaining the effects of underpinning or invert slabs. Large stones are placed on the river bed at the base of the piers to protect against scouring. The size of rocks depends on their shape (to provide good interlocking) and the speed of water flow. It is recommended that they are placed 0.5m below normal river bed level and may be embedded in concrete if the engineer deems necessary. In faster flows they should extend across the river bed to the opposite pier.

The method is very low cost and simple to design and install. Traffic is not disrupted except in the case the rocks are lowered by equipment on the road service; a very short disruption. It is unlikely services will be affected.

A particular advantage is that the rocks can be quickly placed or removed. If, for instance, there is a period of unusually high and fast water flow, stone pitching is a good emergency intervention which may even last long term. On the other hand, adding large rocks to water flow can significantly alter the way it flows and cause negative effects. With stone pitching, the rocks can easily and quickly be removed to prevent these negative effects.

A water resources engineer is recommended in the design and placement of stone pitching.
Visual aspects of the bridge are not affected and the intervention is not seen after completion.

6.5.16 Micro-piling

Micro-piling is useful for providing additional support to settling foundations or load capacity where an increase in loading is expected (or the demand is already greater than the supply of load capacity).

Stabilization of the structure from lateral foundation movement is possible as well. Micro-pilling is suitable for use on bridges with rotted out timber foundations with appropriate precautions. Applications in either dry or wet crossings are acceptable. In some cases, the piling will protrude through the full depth of the pier to help support a reinforced slab that is placed across the road surface (as can be seen in Figure 6.28). Piling should not be used when foundation settlement is due to scour, unless in conjunction with other methods. The piles should be bored through and cast into the existing abutment or pier to provide continuity. Alternatively, the piles may be driven beside the piers or abutments and tied in appropriately.

Boreholes may be drilled through the fill, or the fill may be excavated and the borehole drilled from the top of the abutment or pier. If the bridge requires repair to the spandrel wall, extrados, backfill or other locations that may require excavation of the fill, it is a good opportunity to accomplish two interventions almost simultaneously.

When boreholes are drilled beside the piers and abutments, proper measures should be taken to provide continuity from the piles to the foundations. While this method may allow easier drilling of the boreholes and less disruption to traffic and services, the design may become more difficult. Connections that transfer shear and possibly moment (if lateral forces are to be resisted) between the piles and piers or abutments are needed in the design. If this method is used for a bridge crossing water, cofferdams may need to be used. However, if the drilling is only going through ground material, it may be possible to use a different drilling technique which would normally cause unfavorable vibrations when drilling through the structure.

In non-cohesive soils a rotary drilling rig may be used and a temporary drill casing should be feed down. The casing allows cooling fluid (usually water) to keep the bit cool and remove the drilled material. The rotary drilling system reduces or eliminates damages to the structure caused by vibrations that are present in other drilling methods. Once a required depth is reached, the borehole is filled with grout (usually sand:cement) and reinforcement is placed. Reinforcement can be one or multiple bars placed in the center of the borehole. The temporary casing can be removed and the necessary grout replenished. In the case of a cohesive soil, the method is done the same except the drill casing is removed before grouting.

To carry vertical actions, piles are drilled vertically. If horizontal (or lateral) actions need to be carried by the piles, they are drilled at an incline as seen in some of the piles in Figure 6.28.

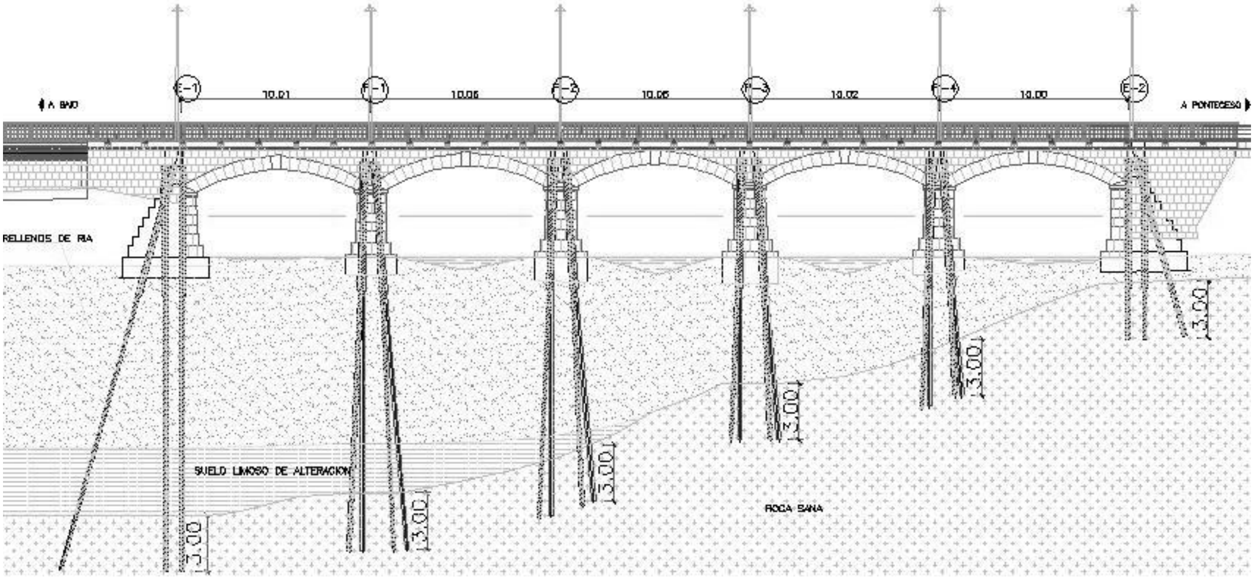


Figure 6.28: Example of micro-piling in abutments with piles both in the vertical and inclined position. These piles also penetrate through the full depth of the bridge to support the road deck. (Leon, 2004)

Piles normally range in diameter from 75-300mm diameter and 10-20m long. A safe working load around 100-300kN is typically acceptable; in rock or dense gravels sometimes up to 500kN. The piles are designed as piles working by skin friction.

Specialist contractors are normally required to carry out the construction. However, the procedure requires no temporary supports and only disturbs traffic for a short period. Piling typically will not cause any risk to the current stability of the bridge and has a quick activation of providing the designed improvements.

Care must be taken to ensure the piles will not damage services which may run through the bridge. Depending on the dimensions of the piles and location of services, additional work may need to be done to rework the services. Grout may also pose a threat to drainage systems or other voids. The use of a sleeve may be considered for pouring of grout if this seems an issue.

Geotechnical engineers are important in the implementation of piling to ensure the proper procedure and design for the particular soil and conditions.

Piling through the abutments or piers is not seen once the process is complete and does not affect the appearance of the bridge. If the case should arise where piling needs to be removed, it can be a complicated and labor intensive task, as well as expensive. Piling which is drilled by the base of the piers may be seen after completion. Often in this case, the piles are covered with concrete, which may also serve as a pile cap (Figure 6.29). This affects the appearance only slightly and maintains the overall authentic look.

Figure 6.29: Concrete pile cap.

6.5.17 Rebuilding

Sometimes a simple solution to major damages in masonry bridges is reconstruction or part reconstruction. This can done to any part of the bridge but some areas can be more difficult than others. This approach is not highly regarded for bridges of cultural and historical importance, as many claim the bridge loses its authenticity. Part reconstruction may be more acceptable when it respects the original aspects of the bridge.

With most reconstruction work, temporary formwork and supports are needed to prevent the loss of bridge integrity. Particularly when the arch ring is reconstructed, heavy formwork is required. Once the formwork is in place, careful dismantling of the section to be rebuilt may proceed. Each piece must be marked and documented. While pieces are removed, any cleaning or similar works on the pieces should be commenced.

Some units may be too damaged to reuse and will require a new piece to be made. When new pieces are made, careful attention should be taken to ensure compatibility in mechanical properties, geometry, and appearance, in order to meet conservation guidelines. In addition, the same recommendations found in the section on grouting for the use of mortars should be applied.

As discussed in the introduction, bridges are a common target in wars and are often destroyed. A bridge may also be destroyed by a natural disaster or other significant event. When these bridges are important cultural or historical structures, it is important to rebuild them with as much authenticity as possible. Any salvageable pieces of the original structures should be incorporated in the reconstructed bridge and new parts should be as similar to the original material as possible. Some people may even encourage the bridge to be rebuilt in similar construction techniques as the original, but is a decision to be made for each case. An important aspect of the bridge (other than stability and safety) is that the bridges appearance is authentic. Many times this might require historical research and study.

As the bridge is being rebuilt, a good opportunity is presented to increase the load capacity or improve the stability of the bridge, compared with the original. The design for improvements should yield to the authentic appearance of the bridge. These additions can be similar to some of the discreet strengthening methods mentioned previously or may be a new design, as this type of work allows more freedom in design.

Reconstruction works will require closure in traffic and services that may still be functional in the bridge. Costs can vary significantly depending on the amount of reconstruction to be done. When only a spandrel wall is being reconstructed, costs are much less than compared with reconstruction of the arch. Costs will also depend on the amount of supplemental work is necessary, such as cleaning dismantled parts or fabricated new authentic looking parts. Time may become another issue in increased costs.

Reconstruction should be considered a last alternative, when other methods will not efficiently repair the bridge or are economically impossible. Reconstruction can be less expensive than some strengthening techniques depending on the individual case.

6.6 Summary and Comparison

The table on the following pages provides a summary and comparison between each technique discussed. The table should serve as a reference to compare common aspects of strengthening and repairing techniques and as a summary of the more detailed descriptions above. It should not be the only means by which to compare and choose interventions. The accompanying description of each technique should be read for understanding, additional resources should be found as needed, and the engineer's discretion for the particular circumstance should be used.

Table 6.2: Summary and comparison of Intervention Techniques

Intervention Technique	Location(s)	Applicable Damages or Faults	Advantages	Disadvantages	Visual Effect
Grouting	• Arch Ring • Spandrel Walls • Parapets	• Ring Separation • Voids • Cracks	• Quick and simple • Little or no traffic disruption • Service disruptions unlikely • Low Cost	• Removal can be tedious and difficult • Possible poor compatibility of old and new	Improvement if applied neatly
Repointing	• Arch Ring • Spandrel Walls • Parapets	• Deteriorated Mortar	• Quick and simple • Little or no traffic disruption • Service disruptions unlikely • Prevents further deteriorations • Low Cost	• Removal can be difficult and damaging • Careful installation required to prevent further damage	Improvement if applied correctly
Injection	• Infill • Backing	• Voids	• Little or no traffic disruption	• Difficult or impossible removal • Risk of damage to services	Little effect if holes are neatly plugged
Replacing Units	• Arch Ring • Spandrel Walls • Parapets	• Deteriorated brick and stone • Loose, protruding, fallen units	• Quick and simple • Little or no traffic disruption • Prevent further deteriorations • Low Cost	• May require temporary formwork	Improvement with carefully selected units
Saddling	• Extrados • Infill	• Inadequate ring thickness • Insufficient load capacity • Spandrel wall movements • Poor load distribution	• Effective for multiple defects • Can be designed to take all structural loads • No headroom reduction • Good for waterproofing • Economical • Visual effect	• Requires road closure • Involves major excavation and reconstruction works; sometimes including the spandrel wall • May require temporary formwork • Heavy disruption of services	Not visible after completion

Intervention Technique	Location(s)	Applicable Damages or Faults	Advantages	Disadvantages	Visual Effect
Sprayed Concrete	• Intrados	• Inadequate ring thickness • Insufficient load capacity • Badly weathered masonry	• Quick and simple • Little disruption to traffic • No service disruption • No excavation or formwork needed • Lower cost than similar methods	• Decrease in headroom • Shrinkage of concrete is likely • Possible separation between existing arch and concrete • Possibility of corrosion when reinforcement is used • Visual effect	Very unsightly effect on appearance; not recommended for bridges of visual importance
Prefabricated Lining	• Intrados	• Insufficient load capacity • Inadequate ring thickness • Badly weathered masonry	• Quick and simple • Low cost • Little or no traffic disruption • No service disruption	• Headroom is reduced • Visual effect • Metal liners can corrode • Possible separation or voids between existing arch and concrete	Unsightly effect on appearance; not recommended for bridges of visual importance
Near-surface Reinforcement	• Arch ring • Infill	• Insufficient load capacity • Loss of structural integrity • Cracking • Deteriorated mortar	• Little or no traffic disruption • Little or no service disruption • Economical • Visual effects	• Corrosion is possible • Difficult to remove intervention if needed	Nearly unnoticeable.
FRP	• Intrados • Extrados	• Insufficient load capacity • Minor Cracking	• Not labor intensive • Long life • Corrosion resistant • Little or no traffic disruption and no service disruption when applied to intrados • Significant increase in load-bearing capacity • Easy removal from intrados • Lightweight	• Traffic and service disruptions when applied to extrados • Difficult removal from extrados	Slightly noticed on intrados; not seen on extrados.

Intervention Technique	Location(s)	Applicable Damages or Faults	Advantages	Disadvantages	Visual Effect
Anchoring	• Arch ring • Infill	• Longitudinal cracking • Ring separation • Detached, tilted or bulging spandrel walls	• Simple • Little or no traffic disruption • No excavation required • Fairly low cost • Visual affects	• Drilling may be challenging • Possible services disruption • Risk of corrosion	Little effect with proper plugging or capping.
Relieving Slab	• Above infill • Road surface	• Poor load distribution • Insufficient load capacity • High lateral forces on spandrel	• Simple design and construction • Good for waterproofing • No under-bridge traffic disruption • Fairly low cost • Visual effects	• Road surface traffic disruptions • Some excavation may be required	New road surface is the only effect.
Replacing Fill with Concrete	• Infill	• Poor load distribution • Voids • Spandrel wall movement	• Simple repair • Visual effect • Easily combined with other repairs	• Requires road closure • Removal can be inefficient and damaging • Questionable cost efficiency	Not visible after completion
Invert Slabs	• Between abutments/piers	• Scour of foundations • Abutment/pier movements	• No road surface disruption • No service disruption • Fairly low cost	• Risk of scour beneath slab • Risk of downstream erosion • Risk of water pollution • Waterway traffic disrupted	Not visible after completion
Underpinning	• Foundation	• Scour of foundations	• Simple design and construction • No road surface traffic disruptions • Low cost • Visual effect	• Necessity of a cofferdam • Labor intensive • Difficult or damaging removal	Not visible after completion

Intervention Technique	Location(s)	Applicable Damages or Faults	Advantages	Disadvantages	Visual Effect
Stone Pitching	• Foundation	• Scour of foundations	• Very low cost • Simple and fast • Easy removal	• May not provide long-term improvements	Not visible after placement
Micro-piling	• Foundation • Abutments/piers • Infill	• Settlements • Insufficient load capacity • Rotted timber foundations	• Fairly simple and quick • Minimum risk to stability during construction • Quick activation • Visual effect	• Traffic disruptions • Service disruptions • Difficult removal	Only concrete pile cap will be seen; otherwise no visible effect.
Rebuilding	• All	• Heavy deterioration • Destruction • Cracking • Almost any defect	• Good opportunity for improving bridge performance for modern loads • Can restore destroyed heritage bridges	• Traffic and service disruption • May compromise authenticity • Can be expensive • Can be labor intensive • May require heavy formwork	Varies; may improve aesthetics but compromises authenticity.

7. CASE STUDIES

Two case studies are presented which demonstrate applications of several strengthening and repairing techniques mentioned in this paper. In the first case study, load capacity is increased and the bridge is widened to meet modern traffic loads. The intervention includes thickening the arch ring, adding additional abutments with micro-piling, and the application of Carbon Fiber Reinforced Polymer (CFRP). In the second case study, heavy damages were found in the bridge due to neglect and increasing live loads. The intervention includes closing longitudinal cracks, stabilizing the arch ring from further longitudinal cracking by means of an anchoring system, stabilizing of spandrel walls, cleaning of vegetation, repointing, and rebuilding of deteriorated masonry.

Both case studies are adopted from the proceedings of the 2004 International Conference on Arch Bridges.

7.1 The Sandro Gallo Bridge – Venice, Italy

The Sandro Gallo bridge is located Venice Italy. It was built in two separate phases, the first in the XIX century and then in first decades of the XX century. The construction originally was constructed with a substantially homogeneous structural arrangement. The bridge consists of a masonry arch of a 0.36 m thickness (three brick layers) in the central part, and of 0.55 m (four brick layers) from the springing to the connection with the abutments. The older abutments are composed by brick and stone masonry, while the more recent areas are mainly built of concrete.

The bridge did not show any signs of significant damages, however, the Venice administration proposed to increase the load bearing capacity of the bridge. Before any intervention, the bridge was estimated to carry only light traffic (cars, buses). The decision was to upgrade the bridge to a 1st category bridge as defined by the Italian standards (maximum load equal to 600 kN on three axles). With the increase in category, the bridge would also need to be widened.

Figure 7.1: View of the bridge from the canal. (Modena, 2004)

Investigation of The Structure

Structural investigation was done by using both destructive and semi-destructive testing. Three core samples, three single flat-jack tests and one double flat-jack test were performed on the structure of the masonry arch. Two other core samples were done vertically at the abutments of the bridge. Preliminary results allowed the definition of the morphology of the masonry arch. The core samples allowed the determination of thickness in the masonry arch at the crown (0.37 m) and at a distance of 1.27 and 0.53 m from the abutment (thickness of 0.47 and 0.55 m, respectively).

In addition, the flat jack tests were performed at different points of the masonry arch at 1.00, 1.70 and 1.90 m from the abutment. The results revealed a moderate state of stress in all of the tested points (0.25, 0.24 and 0.25 MPa respectively) and the masonry structure showed a good compressive strength of about 2.00 MPa.

The corings at the abutments were to determine morphology of the underlying structures and the soil conditions. The cores showed the presence of a 1.00-1.60 m layer of gravel, sand and cobblestone fill under the road surface on both corings. The foundations were found to have different characteristics.

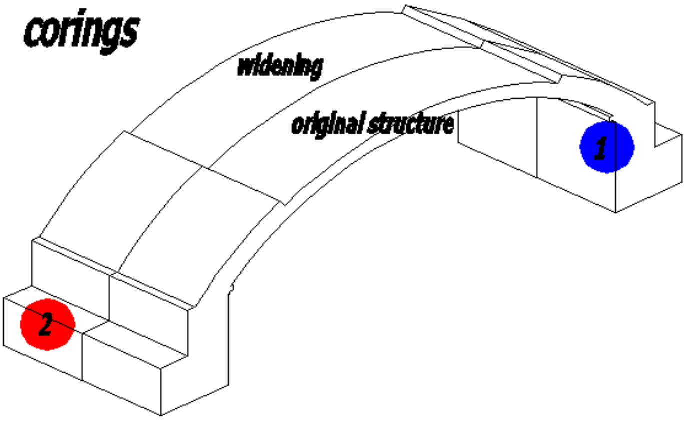


Figure : Coring Locations. (Modena, 2004)

The first core sample, under the filling, indicated the presence of a brick/trachyte masonry with a poor quality mortar, from -1.00 m below the road surface to -5.90 m, where the lowest level of the foundations was found. The second sample was done on the structure where the probable widening of the bridge was planned. It showed a 0.40 m thick concrete slab and a 0.90 m thick underlying brick masonry in poor condition. The related abutment was found to be composed of mass concrete of 2.70 m thickness in fair condition.

The soil underneath was investigated to a depth of 15.00 m below the level of the foundations. The core sample determined a sequence of silty sand and clayey silt. Between the depths of -6.00 and -7.50 m, a timber pile was found.

The Repair Intervention

The aim of the intervention was conservation of the structure of the bridge and the increase of the load- bearing capacity. The upgrading utilized the existing structure, was strengthened by using innovative and traditional materials, and is proposed to allow possible removable or substitutable intervention techniques in the future.

The central part of the arch span which only had a thickness of three bricks was widened by one more layer of bricks. This is a method of thickening the arch ring to improve the load capacity of the bridge by allowing the thrust line a larger geometric boundary. To improve the continuity and shear transfer between the old and new layers, metallic dowels were used with epoxy resin.

A new reinforced concrete foundation to bear the extra load arising from the increase in traffic loads was added behind the abutments and was positioned on micro-piles. At the interface of the old and new abutment, a saw tooth joint was created to improve the transfer of thrust to the new abutment. The micro-piles are arranged both vertically and at an angle to resist vertical and lateral loads.

It is interesting to note the addition to the foundation on the inside of the arch. A small slab was added to the existing foundation with sheet pilling underneath. These can exist as a precaution to prevent scour of the existing foundations and also as added stability for the existing foundations with the newly added mass on the external side of the foundation.

The improvements of the new geometry provided a safety factor of 2.24, when a limit analysis assessment was performed analytically. To meet the Italian standards, a further increase of the safety factor is found in the application of uni-directional high resistance CFRP (Carbon Fiber Reinforced Concrete) strips at the extrados of the masonry arch. The applied CFRP has a Young's modulus of E_{cfrp} = 2.3E+05 MPa, a tensile strength of $f_{t,\ cfrp}$ = 3430 MPa, and an ultimate tensile strain of ε_{cfrp} = 1.5%.

The ends of the strips were connected by epoxy-based adhesive to the new reinforced concrete abutments, which were previously coated with an anti-shrink, thixotropic, high mechanical characteristics mortar. Fibers were also glued with epoxy resin to the arch structure, whose surface is regularized by the presence of the new layer of bricks and the application of a hydraulic-lime based mortar layer (f_{cm} = 18 MPa, f_{bm} = 7.8 MPa).

As mentioned earlier on principles of strengthening masonry arch bridges, the addition of a high tensile strength material to the arch ring can allow a significant load-capacity increase for the bridge, without increasing the physical thickness of the arch ring. The CFRP carries the tensile forces that are subjected to the arch when the line of thrust begins to protrude outside the boundary of the arch ring thickness and would otherwise cause a hinge to develop in the absence of tensile resisting material.

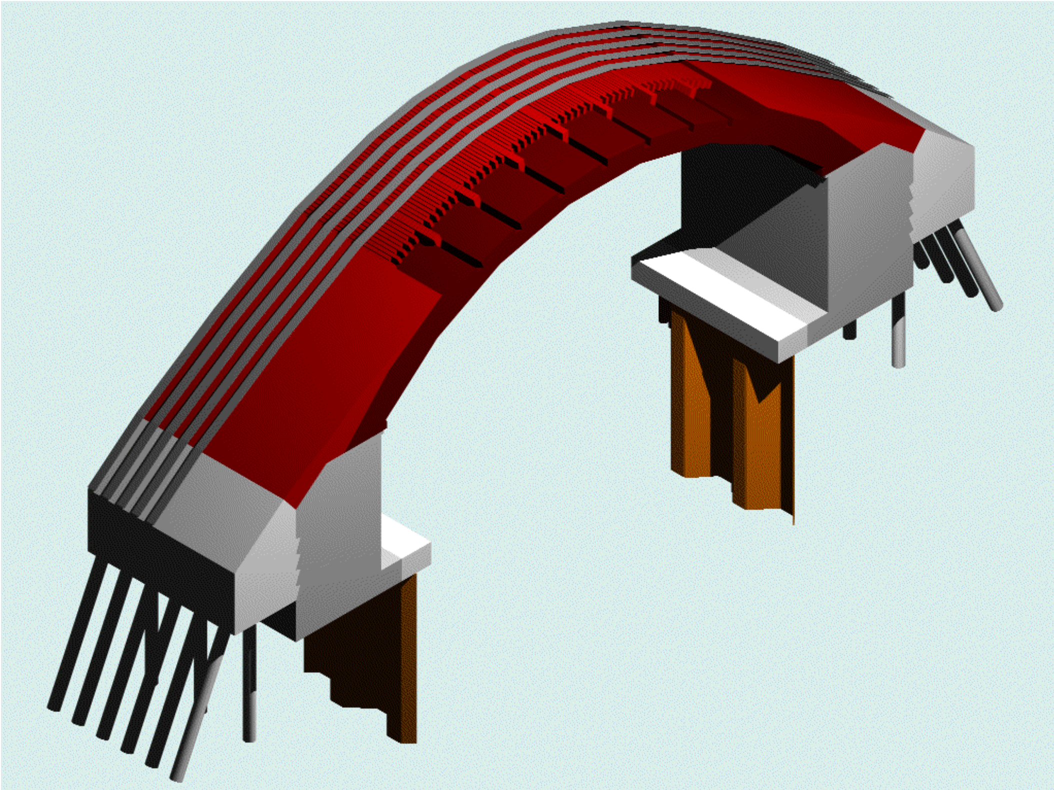


Figure 7.2: Rendering of new structural arrangement.

Description of the Intervention Phases

The works on the lower structure of the bridge include the insertion, at the level of the abutments, of timber piles 2.00 m in length, connected at their upper end with a reinforced concrete beam, to avoid the possible damage on the submerged structures.

The intrados of the masonry arch will be restored in by cleaning of the surface, removal of the plaster, substitution of the deteriorated bricks with new ones, excavation of the deteriorated part of the mortar joints and repointing with proper hydraulic-lime based mortar, and final repositioning of the plaster. The hydraulic-lime mortar had a strength of f_{cm} = 18 MPa and f_{bm} = 7.8 MPa.

The majority of the interventions were done at the extrados and divided into efficient phases as follows:

1 - Excavation of the internal filling above the arch and preparation of the horizontal grade for positioning the concrete foundation beam;

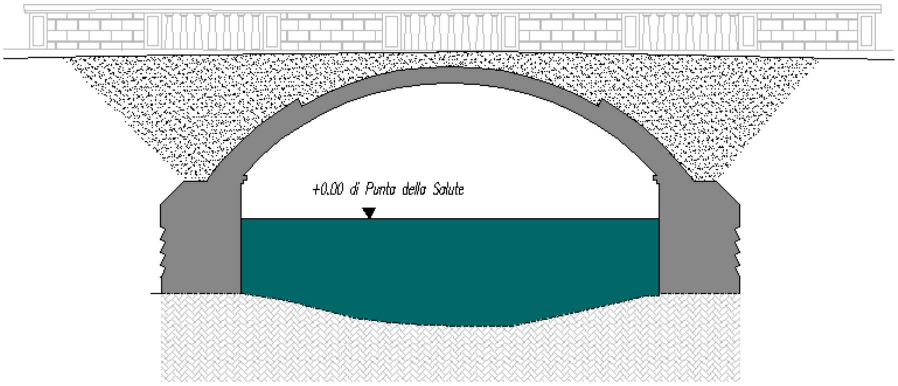


Figure 7.3: Plan view showing area of excavated fill. (Modena, 2004)

2 - Installation of the sub foundation micro-piles with a diameter of 200 mm and an internal reinforcement composed by a steel hollow bar (external diameter 101.6 mm, thickness 10 mm).

3 - Casting of the horizontal reinforced concrete beams, pouring of concrete abutment;

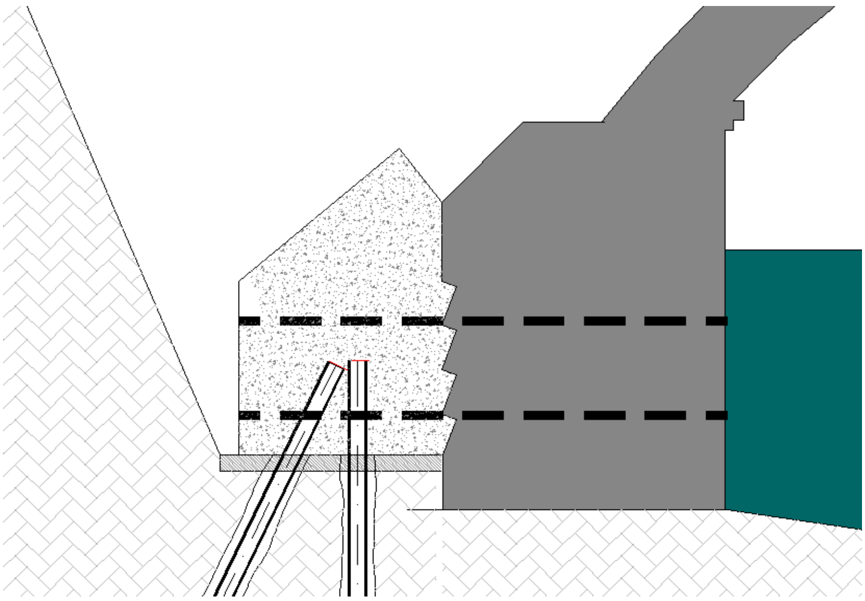


Figure 7.4: Detail of concrete abutment and micro-piles. (Modena, 2004)

4 - Construction and connection of a new masonry arch layer above the abutment and springers to the old masonry, regularizing the extrados structure;

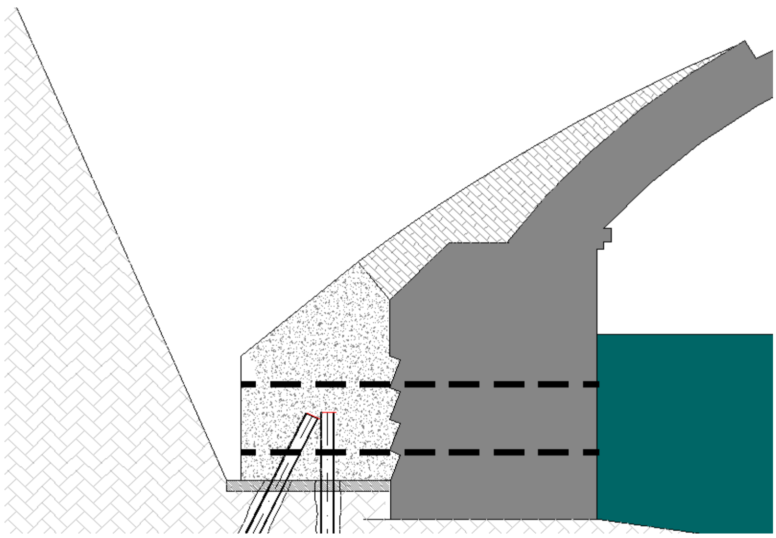


Figure 7.5: Addition of new masonry arch layer. (Modena, 2004)

5 - Thickening of the existing masonry structure in the central part of the span, positioning of brick units orthogonal to the axial line of the arch used as connectors between the old and the new masonry, and positioning of steel rods of 20 mm diameter with epoxy resins, for the same function;

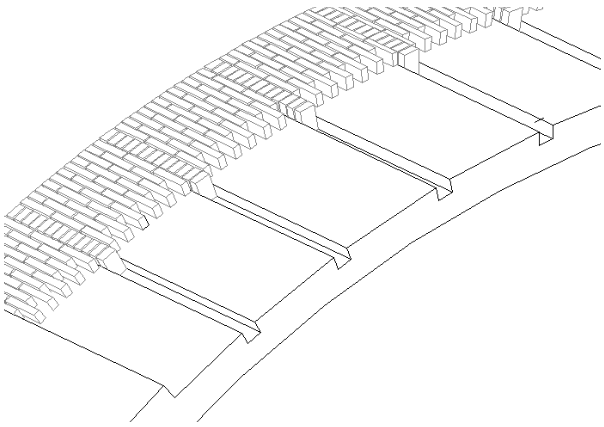


Figure 7.6: Scheme for thickening existing masonry arch. (Modena, 2004)

6 - Preparation of the upper surface of the arch and placing of the CFRP: removal of damaged bricks and substitution with new ones, excavation of deteriorated mortar joints and repointing with the same hydraulic-lime based mortar used at the intrados, application of a hydraulic-lime based mortar layer and smoothing of the external surface, positioning of the Carbon Fibers with previous application of primer and epoxy adhesive, final protecting cover.

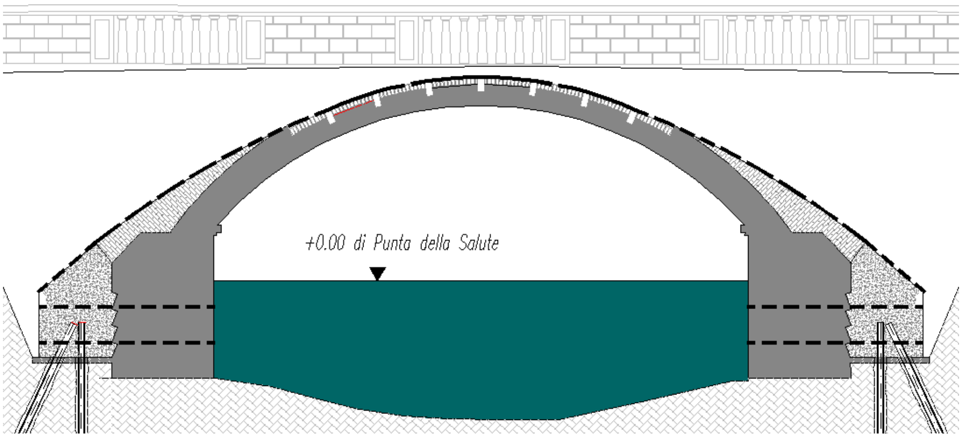


Figure 7.7: Design cross-section. (Modena, 2004)

7 - Re-filling the upper part of the arch with the same material that was removed;

8 - Closing of the 1st phase and moving of the work site to the 2nd symmetric part of the bridge.

The foundation reinforced concrete beam is cast adjacent to the old masonry structure, transferring the extra thrusts coming from the increased live loads to the micro-piles. The micro-piles are disposed in two rows per side; those on the internal row are vertical while those of the external line are inclined with an angle of 25° with respect to the vertical plane.

Conclusion

The construction of the intervention on the bridge was completed at the beginning of 2005 and proves to be an effective intervention. Although the process required long road closure, the bridge is remains in good condition and meets the requirements of Italian codes. The interventions were compatible with the existing material and have not caused any problems. In addition, the intervention did not affect the aesthetic appearance of the bridge. In fact, the cleaning of the exterior improved the aesthesis. Thus, a successful intervention was designed and constructed which follows the conservation guidelines and improves the performance of the bridge.

7.2 Donim Bridge

Donim Bridge is located in Guimarães, Portugal across the Ave River and is believed to have been built during the 15th or 16th century. Donim Bridge served as an important structure for the Minho road network in ancient times. Over the many years, the bridge has lost its significance and it is mainly used for local travel.

The bridge consists of a flat roadway, supported by three semicircular stone masonry arches of different spans (6.6 m, 11.8 m, and 9.4 m), as shown below. The bridges full length is 62.0 m and has a roadway width of 3.4 m. The central arch has the largest span and is supported by two massive piers with two triangular cutwaters at the upstream side and two rectangular cutwaters at the downstream side. It was discovered that both piers rest on solid rock. On the right shore it is possible to find an additional arch serving the purpose of a flood arch (A4), with a span of 2.7 m.

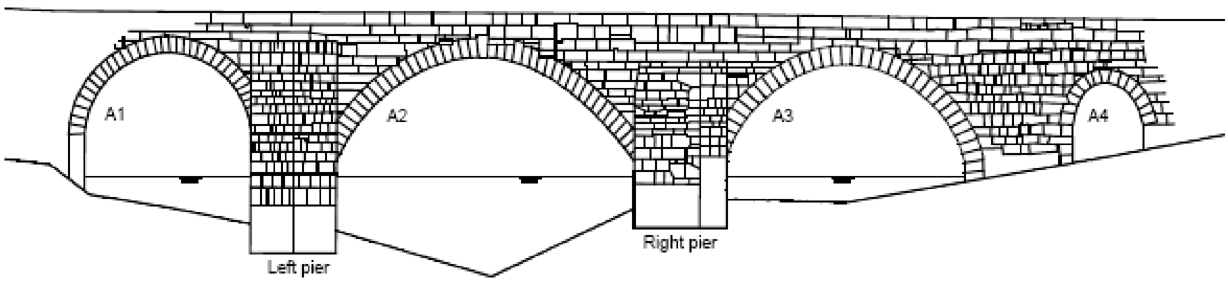


Figure 7.8: Donim Bridge Elevation; upstream side. (Oliveira, 2004)

The spandrel walls and parapets were also built with stone masonry, but maintenance and repairing works through the years have introduced some other materials into the structure. The parapet wall was partially rebuilt with concrete blocks and the pavement was replaced with granitic paving-stone during the 20th century.

As with any conservation project, research, investigation and a complete survey of the bridge were completed before continuing. Particularly for the uncertain safety conditions of this bridge, careful attention was taken during the investigation and survey. Local authorities also requested a definition of a set of remedial measures, compatible with the modern principles of conservation, in order to restore the safety and stability of the structure.

The investigation and survey of the bridge presented a pronounced damage state. Both the left arch (A1) and the flood arch (A4) had extensive longitudinal cracking, clearly visible at the intrados (Figure 7.9). The right pier had significant damage, where some stone blocks were cracked and a foundation stone was missing. The vegetation, which had spread over much of the bridge, caused severe damages to the right cutwater. The spandrel walls were subjected to lateral movement and were clearly out of plumb. Damages have been a result of the lack of maintenance in conjunction with increasingly heavy loads that cross the bridge.

(a) (b)

Figure 7.9: Longitudinal cracking in (a) arch A1 and (b) arch A4. (Apreutesei, 2005)

Figure 7.10: Cracks and vegetation in the right cutwater. (Oliveira, 2004)

To determine the assessment of the safety conditions for the bridge, a numerical analysis was carried out aiming at the understanding and justification of the damages observed. The survey of the bridge provided the necessary geometrical data for an accurate analysis. A three-dimensional finite element model was created, where both the non-linear material behavior of masonry and the infill were considered in the analysis. The results allowed for an understanding of the behavior of the infill and spandrel walls and to justify a valid reason for the observed longitudinal cracking at the intrados of the arches. Both the detailed visual inspection and the numerical analysis lead to the clear conclusion that strengthening of the bridge was necessary. The main aim was to offset the outward movement of the spandrel walls, to prevent their failure and to stop the progression of the longitudinal cracking along the arches, in order to re-establish the safety conditions of the bridge. The intervention was thus focused on the structural strengthening of arch A1, arch A4, and the right pier cutwater.

Before intervention began, three primary pre-construction tasks were necessary. First, the bridge was closed to all traffic to prevent any further damage to the bridge and allow for excavation of the fill. Second, in order to allow access to the pier and cutwater as well as the intrados of arch A1 and A3, water was blocked and diverted through the middle arch, A2, only. Heavy stones and sand were pushed into the water to create the barrier. The third task was to remove the vegetation that blocked access to the repair areas. Removal and cleaning of the surface also proceeded throughout the intervention.

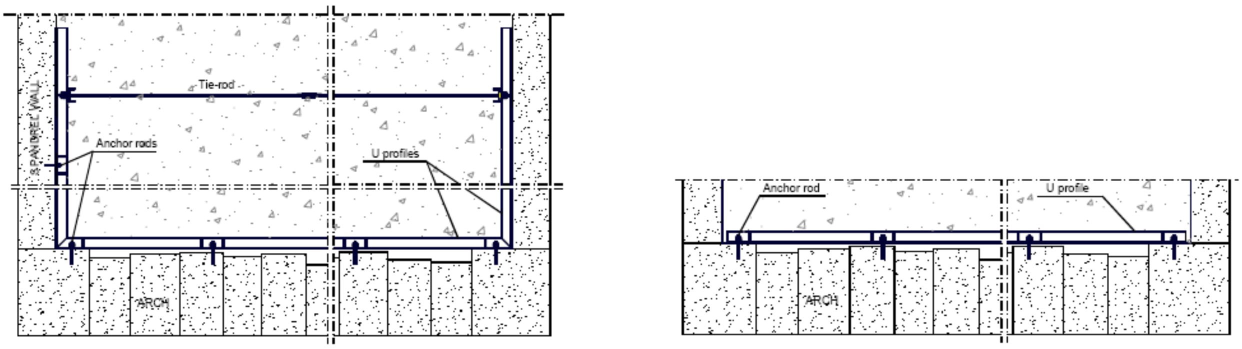
Figure 7.11: Blocking water flow. (Apreutesei, 2005)

In an attempt to keep foot traffic from being disrupted, a temporary bridge was built for foot traffic only. A truss over bridge was constructed for this purpose, parallel to the existing bridge. However, due to rainfall and rising water levels, the temporary bridge was damaged. Another temporary bridge was built across the cutwaters of the existing stone bridge and proved a better and safer solution. Construction of the intervention, however, was delayed while the second bridge was constructed.

To reduce the enormous longitudinal cracking in the intrados of arch A1 (crack widths greater than 8 cm) and return masonry to its original spacing, the infill above arch A1 was removed and the voussoirs reset. Rope-stretchers placed along the intrados of the arch were utilized to push the voussoirs together slowly. During this procedure, temporary formwork was necessary to stabilize the span (installed prior to excavation; Figure 7.12). In addition, five temporary tie bars were installed to restrain the further outward movement of the spandrel walls during construction. These bars went across the full width of the bridge at the level of the parapet.

The strengthening technique used was an anchoring system. Six stainless steel U profiles were fixed to the extrados of the arch and to both spandrel walls with anchor rods (Figure 7.13). A stainless steel tie rod, with a diameter of 16 mm, was placed at the top of the vertical profiles and tightened with a dynamometric wrench to bind the spandrel walls together and reduce considerably the amount of bending. Close to the crown, the proximity of the pavement allowed only the use of a U profile clamped to the arch with anchor rods. After the completion of these works, the infill was replaced and the temporary formwork was removed.

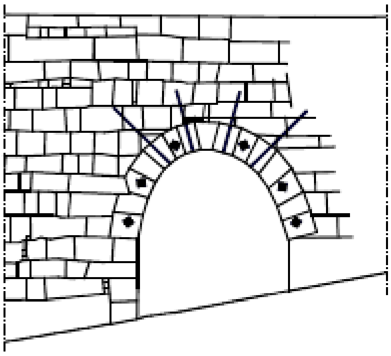
Figure 7.12: Temporary formwork. (Apreutesei, 2005)

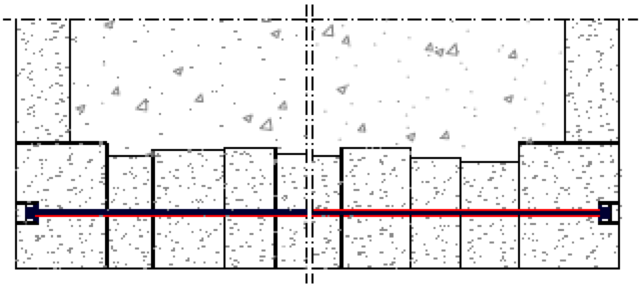


(a) (b)

Figure 7.13: Strengthening of arch A1 with U profiles; (a) general cross-section; (b) cross-section near crown. (Oliveira, 2004).

The cracking observed in the flood arch was less severe, with maximum crack widths lower than 4 cm. Here, the objective was not to return the arch to its original geometry but to prevent any further movement of the arch and to assure its stability. Six horizontal anchors were chose to run across the full width of the bridge, secured with cylindrical anchorage plates at each side of the arch (Figure 7.14).





(a) (b)

Figure 7.14: Flood arch strengthening system; (a) anchor scheme; (b) horizontal anchors. (Oliveira, 2004)

After an oversized hole was drilled using a rotating cutting device, a stainless steel rod with a 16 mm diameter encased by a sleeve, was placed in the hole and subsequently grouted under low pressure. The use of the sleeve increased the efficiency of the anchor system since it expanded, preventing the injected grout from being lost in voids within the structure, or escaping through cracks.

(a) (b)

Figure 7.15: (a) Drilled hole with sleeve and rod in place; (b) Rod with anchorage plate. (Apreutesei, 2005)

The rods were not pre-tensioned, but only tightened by using a dynamometric wrench. After the anchors were installed and grouted, a cylinder of stone from the drilling was used to plug the hole. This allowed little effect on the visual appearance of the bridge.

For the connection between the arch and spandrel walls a similar process was developed. Four stitching anchors on each side of the arch (Figure 7.14a), ranging between 1200 mm and 1500 mm in length, were used to promote the continuity between the external voussoirs and spandrel walls, and prevent ring separation from the spandrel. This is also called radial pinning.

The high level of damage found in the right cutwater, with several stones cracked and miss positioned due to movements, was repaired by dismantling of the most deteriorated areas. Local rebuilding was done using the same stones or ones with very similar properties from the region. This ensures visual and mechanical compatibility. During the rebuilding, every third course implemented stainless steel cramps to connect the stones to each other. The link between two consecutive courses was achieved through the use of vertical stainless steel latches.

Figure 7.16: Rebuilding the right cutwater. (Apreutesei, 2005)

Figure 7.17: Stainless steel cramps. (Apreutesei, 2005)

In order to prevent washout of fines, to help waterproof the structure and help prevent future deterioration, repointing was applied to any joints showing degradation. A compatible lime mortar was selected with similar properties and appearance for the repointing.

Figure 7.18: Repointed joints. (Apreutesei, 2005)

Conclusion

The intervention in the Donim Bridge has shown to be successful, as it has improved the performance of the bridge and all methods were in compliance with the conservation guidelines. The structure was improved in its aesthetic appearance and little sign of the actually intervention are seen. The disadvantages were the disruption to traffic and heavy construction work required. However, these were the works found to be the most efficient and economical by the engineer in the weight of these disadvantages and thus it is an appropriate intervention.

8. CONCLUSION

Masonry arch bridges are found throughout the world. Many have both an important function for the infrastructure and an important heritage value. Due to prolonged weathering, environmental forces, wars, increased live loads, and other causes of damages, a large number of these bridges require repair and strengthening works. The designer of a conservation project should proceed in such a way so as to respect the need for both performance improvements and cultural heritage preservation. The ideas in this paper were presented in such a way so as to help the engineer choose an intervention which reflects these two criteria.

Conservation projects should first begin with historical research, inspection and geometrical survey of the bridge. These are important steps in understanding the condition and behavior of the bridge, and the information collected will allow the engineer to assess the bridge and determine the best course of action. An accurate geometrical survey will provide the means to perform a simple analysis empirically or with basic software such as RING 2.0. Sometimes it will be necessary to determine more specific properties for a numerical analysis (such as finite elements). This may require further investigation of the materials in the structure by means of non-destructive or perhaps destructive testing.

With the information from the investigation and analysis, the engineer will have an understanding of the bridge’s behavior and the cause of damages or faults. It is important to ensure that the cause of the problem will be addressed and rather than only a symptom of the problem. It will now be possible to determine an appropriate intervention with a result that is compatible, is respectful to conservation principles, is performance improving, is durable, and is cost effective. It should be an aim to solve as many problems in the bridge as can be done at the same time, or at least can be done in a logical sequence. Table 6.2 summarizes and compares the different methods discussed in this paper for strengthening and repairing of masonry arch bridges. This table can be utilized during the process of intervention choice to highlight the main advantages and disadvantages, and the relevance of each method.

In addition to how the intervention affects the bridge, consideration should be given to the way it may affect the surrounding environment during and after construction. An intervention should minimally affect traffic or services on the bridge during construction. The natural environment should be preserved and any risk of pollution to the environment must be prevented or contained.

In conjunction with the any strengthening and repairing techniques, consideration of adequate waterproofing and drainage should always be included. The effects of water on masonry structures, particularly on the internal materials, contribute to a significant portion of the structural problems that may occur over a prolonged period of time. Regular general maintenance of a bridge is also important in preserving the integrity and stability and preventing further damages from incurring.

By following a logical and careful process of bridge conservation and using repairing and strengthening techniques that follow conservation guidelines such as those presented in this paper, successful intervention which respects the needs for performance improvements and cultural preservation may be performed.

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10. APPENDIX A: FURTHER TOPICS AND REFERENCES

This appendix references sources for further information on the assessment and analysis of masonry arch bridges. This is not a complete index of available sources, but only a small compilation the author has found useful or interesting during research.

References for many topics surrounding masonry arch bridges can be found in the proceedings of the International Conference on Arch Bridges. At the time of writing, the following proceedings were available:

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